1969

Recent Carbonate Sedimentation, North Sound, Grand Cayman Island British West Indies.

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ROBERTS, Harry Heil, 1940-
RECENT CARBONATE SEDIMENTATION, NORTH SOUND, GRAND CAYMAN ISLAND, BRITISH WEST INDIES.

The Louisiana State University and Agricultural and Mechanical College, Ph.D., 1969
Geology

University Microfilms, Inc., Ann Arbor, Michigan

RECENT CARBONATE SEDIMENTATION, NORTH SOUND, GRAND CAYMAN ISLAND, BRITISH WEST INDIES

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Geology

by
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B.S., Marshall University, 1962
M.S., Louisiana State University, 1966
May, 1969

ACKNOWLEDGMENTS

The completion of this problem is due to the summation of support and cooperation from several individuals and organizations. The study was supervised by Dr. Clyde H. Moore, Jr., of the Department of Geology, Louisiana State University, and financially supported by Coastal Studies Institute, under contract to the Geographic Programs, Office of Naval Research, Project No. Nonr 1575(03), Task Order No. NR 388 002. A special debt of gratitude is owed to Dr. Moore and Dr. W. G. McIntire, Director of the Institute for their assistance throughout this project.

Preparation for the field research associated with this study took many hours of planning and labor. For this work and for expert instruction in the use of SCUBA equipment the writer wishes to thank Norwood H. Rector.

Field operations were expedited by the friendly cooperation of the citizenry of Grand Cayman Island. Sam Ebanks is recognized for his field assistance and willingness to work long hours, all of which contributed significantly to the completion of the project.

Dr. J. K. Rigby has the grateful appreciation of the writer for helping to familiarize him with organic communities of the reef and reef-associated environments.

Instruction in laboratory techniques concerning atomic absorption and X-ray diffraction analyses by Dr. G. K. Billings and Dr. Ray Ferrell, respectively, is sincerely appreciated.

Alvin Phillips was kind enough to assist in the identification of Foraminifera.

The writer would like to thank the Department of Geology for financing the making of thin-sections. Thanks also go to Humble Oil and Refining Company for making additional thin-sections for this study and to Mr. C. S. Fleishman for arranging to have this accomplished.

To Dr. Prentiss Schilling and the Louisiana State University Computer Center grateful thanks are extended for adapting programs and analyzing data during the course of the study.

Appreciation is due to the members of the writer's examining committee - Dr. G. K. Billings, Dr. J. C. Ferm, Dr. C.H. Moore, Jr., Dr. B. F. Perkins, and Dr. W. G. Smith - for cirtically reviewing the manuscript.

Shirley Gerald and Lois Henderson were responsible for helpful editorial criticisms and drafting, respectively. Their time and assistance are gratefully acknowledged.

Finally, gratitude is expressed to the writer's wife, Suzie, for her patience and helpful assistance throughout the entire project.

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ABSTRACT

Assessment of variability in selected mineralogical, chemical, and petrographic parameters as a function of sedimentary environment was made by analyzing 70 samples collected from the major environments of North Sound, Grand Cayman Island. Sediments accumulating in this shallow saline lagoon are exclusively carbonates. The many grain types composing the sediments are derived from a variety of plant and animal communities. Physical and biological destruction of members of these communities results in accumulation of skeletal sands near the reef which grade lagoonward into lime muds. From high energy conditions near the reef to the quiet grassy interior of the lagoon, four major environments were designated: (1) reef-shoal, (2) shore zone, (3) grass plain, and (4) restricted lagoon. Statistically significant differences in sediment parameters confirmed the validity of these environments.

The constituent grains -- coral, coralline algae, and composite grains -- are most indicative of reef-shoal sediments. Composite grains of this environment represent the only evidence of recent inorganic carbonate precipitation in the basin of deposition. These cemented aggregates occur in localized areas associated with major breaks in the fringing reef. The shore zone is characterized by Pleistocene (?) rock fragments and cryptocrystalline grains. Halimeda and Foraminifera are most abundant in the grass plain, and a relatively high percentage of molluscs distinguishes sediments of the restricted lagoon.

Mineralogical differences between environments reflect types and relative percentages of constituent grains. Three carbonate mineral phases were recognized (X-ray diffraction): aragonite, high-Mg calcite, and low-Mg calcite. Aragonite is most concentrated in sediments of the restricted lagoon, a fact which can be attributed to an increase of molluscan debris at the expense of Foraminifera. High-Mg calcite is most concentrated in the grass plain and results from the incidence of many Foraminifera. Low-Mg calcite is most abundant in the shore zone. Sources for this mineral are limestones from near-shore outcrops and the sound floor.

Concentrations of three HCl-leachable cations (Mg, Sr, and Na) were investigated in each sediment sample (atomic absorption spectrophotometry). Mg and Sr concentrations are generally covariant with proportions of high-Mg calcite and aragonite, respectively. The grass plain has the highest Mg concentration owing to a large proportion of high-Mg calcite Foraminifera. The restricted lagoon is highest in aragonite; however, reef-shoal sediments exhibit a greater Sr concentration. Corals of the reef-shoal concentrate Sr to a greater extent than do molluscs of the restricted lagoon. Na systematically decreases in sediments from near the reef to the lagoon interior. This pattern seems to be related to a cumulative effect caused by differential acceptance of Na by various carbonate skeletons. The fact that coral concentrates Na to a greater extent than *Halimeda* is primarily responsible for the gradient.

In all environments high-Mg calcite is increased in the fine sediment fraction at the expense of aragonite. Field and laboratory evidence concerning stability of carbonate minerals show that aragonite is less soluble than high-Mg calcite under shallow marine conditions. Therefore, an abundance of high-Mg calcite in the fines cannot be attributed to preferential solution of aragonite. Considering the abundance and non-durability of high-Mg calcite skeletons (coralline algae, echinoids, Foraminifera, serpulids, and others), it appears that differential physical particle size reduction is the most reasonable explanation for this phenomenon.

General covariance of mineral and chemical characteristics between fine and coarse size fractions suggests that the primary origin for the fines is *in situ* degradation of coarse material.

INTRODUCTION

Variation in contemporaneously deposited carbonate sediments serves as a basis for environmental characterization of recent carbonates as well as an underlying criterion for lithic correlation and environmental interpretation of ancient limestones. A complex interaction of biological, chemical, and physical factors determines the nature and extent of this variation within any particular basin of deposition (Ginsburg, 1956). Although many studies of recent carbonates have been concerned with the regional relationship between sediments and the environments in which they were deposited, variation in sediments between environments within small basins of deposition has mostly been described in very general terms. It is the purpose of this paper to offer an assessment of the variation in surface carbonate sediments between major environments within North Sound, a small, shallow-water basin, of limestone capped Grand Cayman Island. Basic data were derived from 70 sediment samples collected from the four major environments constituting the basin of deposition. Selected chemical, mineralogical, and petrographic parameters were measured and statistically evaluated. The degree to which the findings of this study are exemplary of other small basins of carbonate deposition is not entirely certain. However, the reefal and lagoonal environments, as well as the marine organisms which manufacture and modify the sediments are typical of environments and organisms reported by many studies of recent carbonates.

Many previous investigations dealing with environmental characterization of carbonate sediments have been primarily concerned with variations on a regional scale. Studies of this type have generated some rather sophisticated models of large-scale variation in carbonate sedimentation from areas such as the Great Bahama Bank and Florida Bay. Although many aspects of the regional models are applicable to small basins, the nature of variation within these basins is not precisely known. North Sound, Grand Cayman Island, is particularly suited for investigation of changes among intrabasinal carbonates. From the high energy conditions near the fringing reef to the quiet-water lagoon distinct environments and communities of sediment-producing organisms are readily apparent. In addition, the low relief of bordering carbonate terrain precludes the influx of terrigenous materials as well as large amounts of eroded ancient limestone. Virtually all of North Sound's sediments are carbonates that have been manufactured and deposited within the basin.

REGIONAL GEOLOGIC AND GEOGRAPHIC FRAMEWORK

Grand Cayman, largest of a group of three small islands, is located in the Caribbean Sea approximately 150 miles south of the Isle of Pines, Cuba, 180 miles northwest of Jamaica, and 450 miles east of Yucatan (Fig. 1). Its dimensions are approximately 22 miles east-west and 4 to 9 miles north-south.

The Cayman Islands are prominences on a submarine ridge, an extension of the east-west trending Sierra Maestra mountain range of southeastern Cuba. The Cayman Ridge is well defined by the 1000-fathom isobath, as shown in Fig. 1. Approximately 200 miles southwest of the Cayman Islands the Misteriosa Bank occurs as a similar projection on the Cayman Ridge but is not exposed above sea level. Two deep basins border the ridge: the Bartlett Trough to the south, with water depths exceeding 3000 fathoms, and the Yucatan Basin to the northwest, with water depths up to 2500 fathoms.

During Miocene time the Cayman Islands were apparently part of Jamaica (Butterlin, 1956), forming an area of shallow seas or possibly a land mass. Significant changes in paleogeography resulted from block-faulting during the Pliocene. The Pliocene and Pleistocene faulting seems to have been primarily responsible for the simultaneous development of the Bartlett Trough and the Cayman Islands (Schuchert, 1935). At this time the Cayman Islands were separated from Jamaica and from each other. Uplift of land areas continued into the Pleistocene, as evidenced by elevated shorelines and

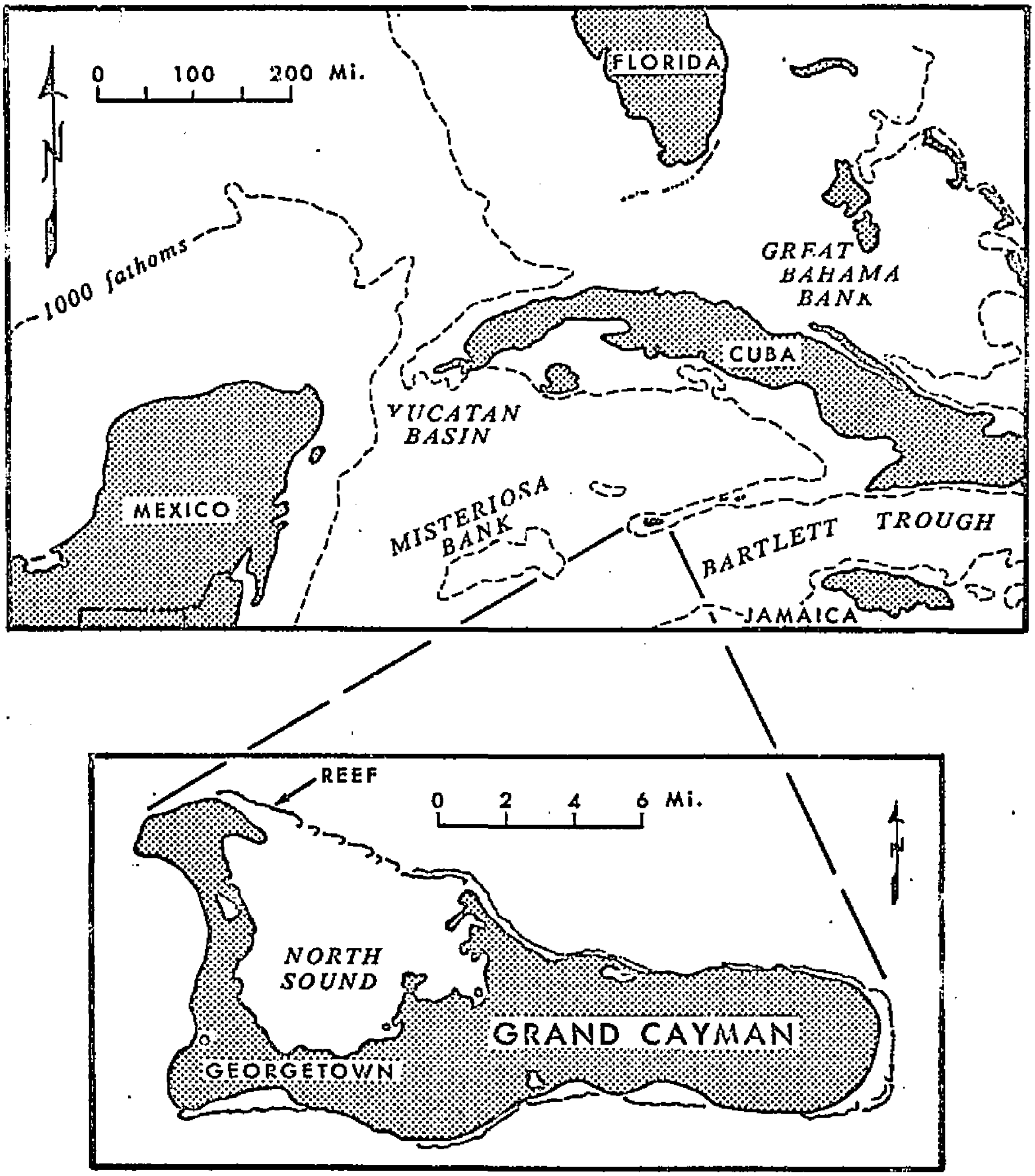


Fig. 1. Location map of Grand Cayman Island.

Pleistocene marine deposits in Haiti and Cuba (Schuchert, 1935). Grand Cayman may have undergone additional uplift at this time, because of its very low relief, it was probably planed by wave erosion in late Tertiary or early Pleistocene times (Doran, 1954).

Topographically, the Cayman Islands are relatively flat; average elevations are only a few feet above sea level. In general, the interior of Grand Cayman is very low, the highest relief being slightly over 60 feet, and occurring on the eastern and northwestern margins. Grand Cayman, like the other two Cayman Islands, is entirely limestone capped. All surface exposures are relatively young and form an emergent platform of Pleistocene and Recent carbonates (Doran, 1953). Solution of the calcareous bedrock produces a small-scale karst topography whose pinnacles, cavities, and other solution phenomena are characteristic surface features of most of the island. Except for the western margin, fringing coral reefs almost entirely border the island, forming numerous shallow-water lagoons. The largest lagoon, North Sound, occurs in the west-central portion of Grand Cayman; it forms a sizeable embayment of shallow saline water. Its waters cover an area of about 35 square miles, and it has an average width of approximately 6 miles.

NORTH SOUND

With the exception of two general areas, the shoreline of North Sound is bordered by mangrove trees growing in relatively shallow water. The northwestern shoreline is formed by a limestone cliff several feet above the lagoon level (Fig. 2). At the northeastern extremity of the sound, the shoreline is a carbonate sand beach. Finer-grained sediments progressively replace the sand southward.

The sound is separated from the open sea by a discontinuous northwest-southeast trending coral reef. Three breaks in the reef serve as main points of entry into the sound for ocean waters into the sound. In general, the water circulation in North Sound is counterclockwise. The main exit for sound water is at the northwest extremity of the sound (Fig. 2).

Submarine contours drawn from 150 leadline soundings show North Sound to be a dish-shaped lagoon with water depths rarely exceeding 15 feet (Fig. 2). The deepest waters occur generally in the center of the sound.

The sound's floor, where it is exposed or was examined through a shallow veneer of sediments, was found to be lithified limestone. Sediments of the northern portion are coarse grained and generally form a thin covering over the limestone floor. Sediments progressively decrease in grain size and thicken toward the center of the sound. Fig. 3 illustrates the thickness of sediments in North Sound as interpreted from 80 probe stations arranged on a grid covering the entire study area. The thickest sediment accumulation is near the southeastern margin of the sound. From this area the sediments

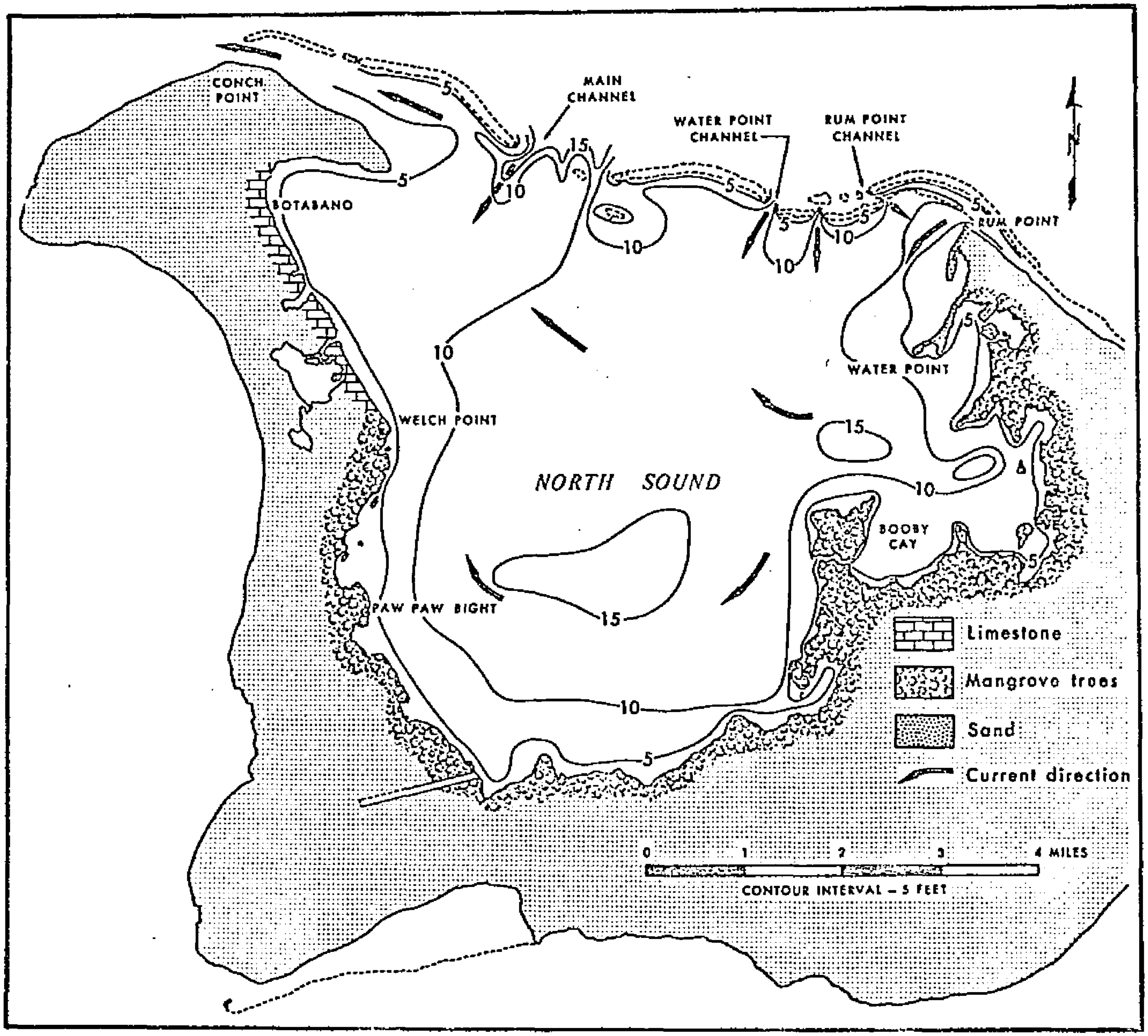


Fig. 2. Bathymetric map of North Sound showing general current pattern and type of shoreline.

generally thin in all directions, with the exception of a relatively thick accumulation in Little Sound. The size and composition of the sediments of North Sound are variable. However, areas of thickest sediment accumulation are areas of predominantly lime mud deposition.

Sediments range from cobble-and sand-sized material near the reef to lime muds in the central and southern regions of the sound (Fig. 3). This distribution and concentration of particles of various sizes has significance in terms of changing depositional environments within the carbonate regime. Ginsburg (1956) shows that variations in the physical environment (bathymetry, areal geography, and hydrography) are reflected in the grain size and particle composition of the sediments. Changes in these physical parameters are coupled with variations in biological and chemical parameters. Therefore, owing to its configuration North Sound offers several environments in which carbonate sediments may originate and be deposited.

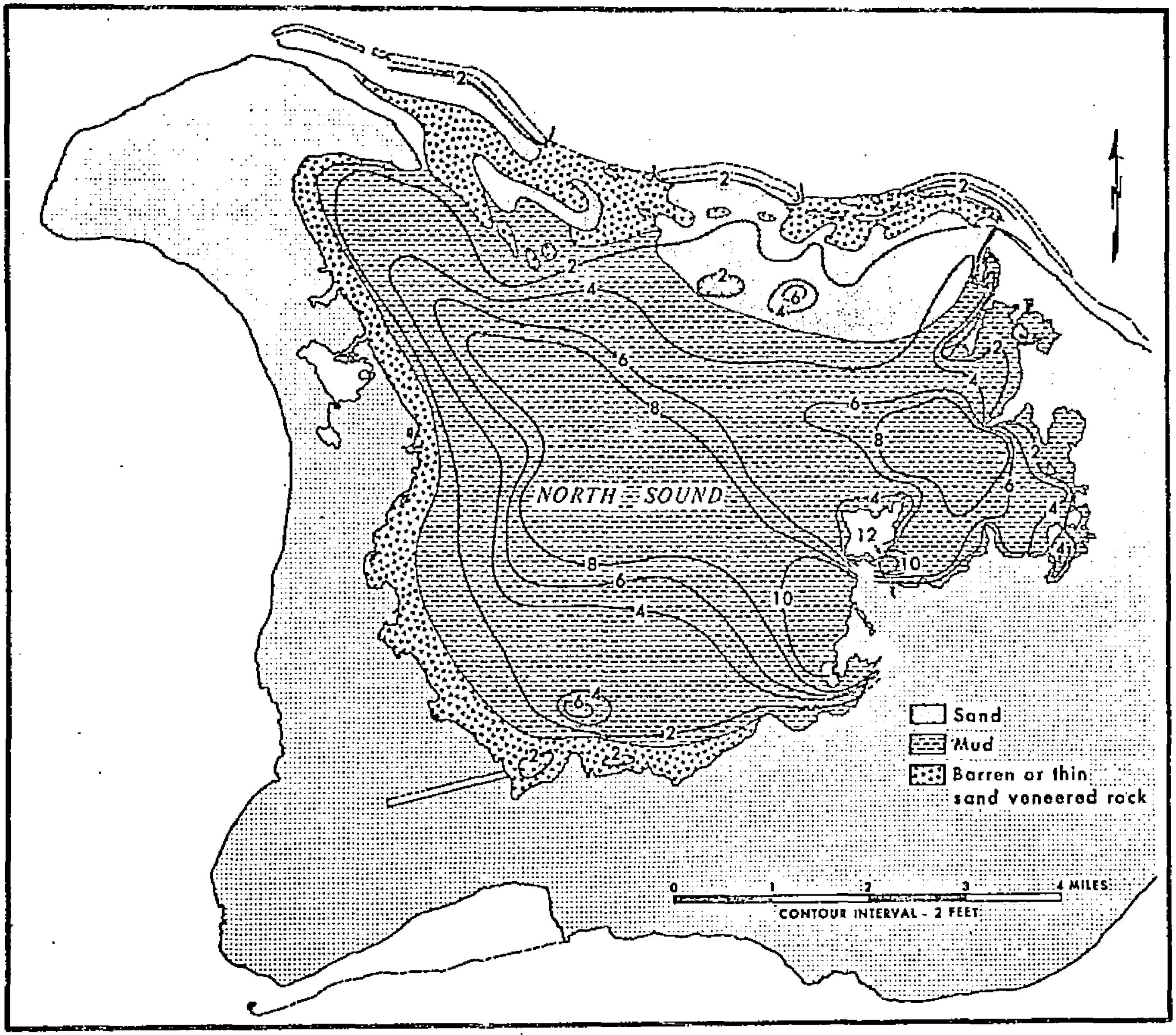


Fig. 3. Thickness of recent sediments in North Sound.

FIELD METHODS

During the summer of 1967 sediment samples and other data on which this study is based were collected.

Sampling was conducted with the purpose of covering all major environments of North Sound. A sampling grid was erected in order to provide complete and systematic coverage.

Field operations were conducted from a skiff. East-west sampling traverses were made across the sound on constant compass bearings. Sample positions were fixed by reading horizontal angles with a hand-held sextant. A series of white cloth targets were used in conjunction with prominent landmarks as points of reference (Fig. 4). Setting the sextant angles on a three-armed protractor permitted use of a method of resection to calculate sample locations.

A total of 70 unconsolidated sediment samples were collected (Fig. 4). The relatively shallow water of North Sound allowed collection of all samples by snorkel diving. At each sample station a short length of plastic tubing was pushed into the bottom in order to collect the upper few inches of sediment. The contents of the tube were then emptied into a plastic bag for storage. In rocky bottomed areas sediments were scooped into the plastic sampling tube.

Observations on sediment-producing organisms were made at each sample locality. The types and relative abundances of benthonic life were noted. Specimens were collected for identification. A mask and snorkel were sufficient for most

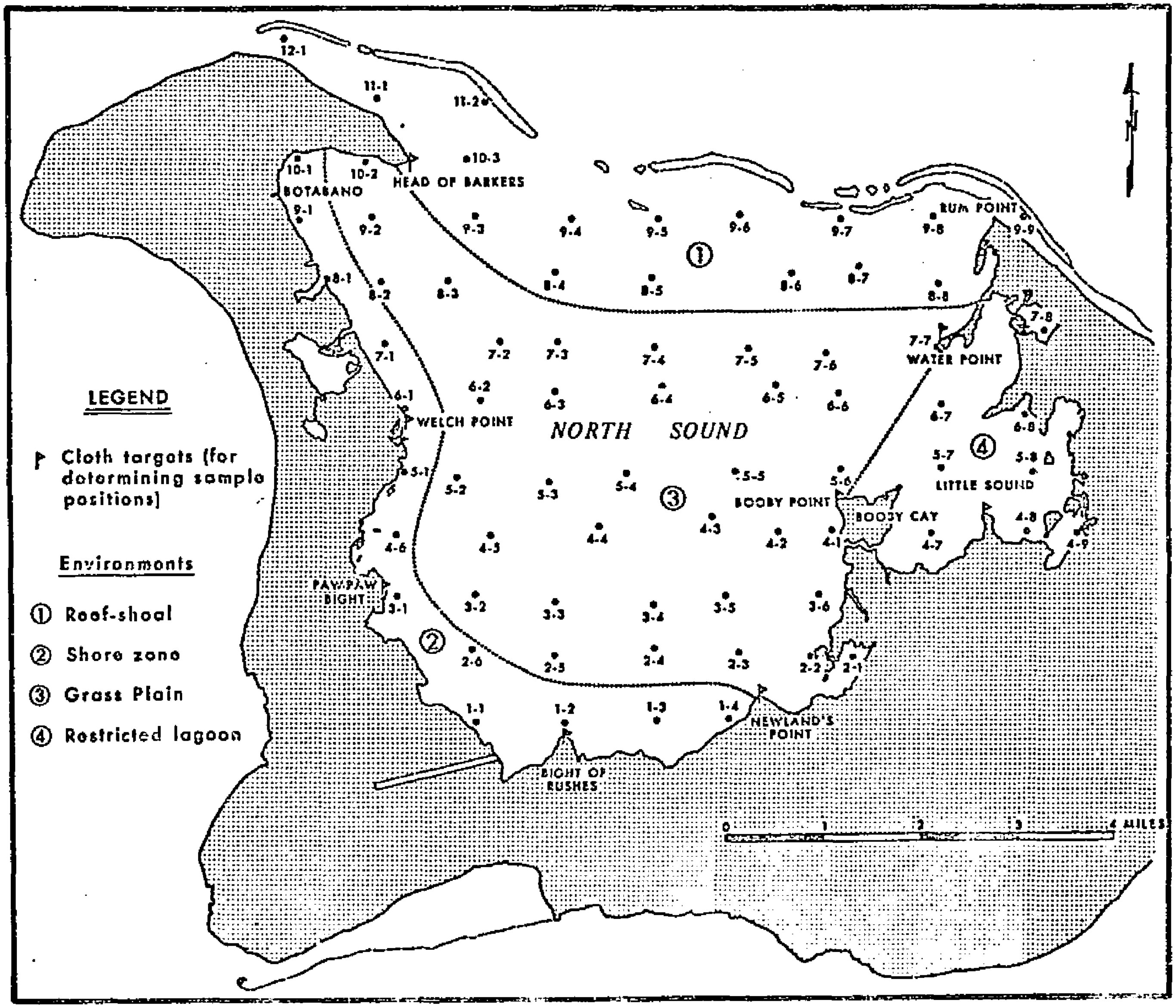


Fig. 4. Sample location map with major environmental subdivisions of North Sound.

observations and specimen collection. Occasionally, SCUBA equipment was used to permit longer periods of submergence for observation and photography. All major environments and benthonic communities were documented on film. After each dive, a tape recorder was used to list pertinent observational data. Additional observations were made by swimming selected traverses across the spectrum of environments in the sound. These traverses were made with the intention of solving particular problems in determining the nature and extent of some of the sound's environments. The results of these data are presented and discussed in conjunction with the ecology of North Sound.

LABORATORY METHODS

GENERAL

Each sediment sample was split into two equal subsamples. One subsample was used for chemical and mineralogical analysis, and the other, for petrographic analysis. The subsamples intended for chemical and mineralogical analysis were wet sieved into two fractions containing particles greater and less than 62.5 microns, respectively. This essentially separated the sand-sized and silt-clay-sized particles. Both fractions were then dried and pulverized until they passed through a 200-mesh sieve. Pulverizing and sieving thoroughly mixed material in each sample. To assure homogeneity, each powdered sample was placed in a plastic container and mechanically shaken for several minutes.

Organics were removed from subsamples designated for petrographic analysis by periodic additions of hydrogen peroxide and by picking out blades of grass and other large pieces of organic matter. Fecal pellets and other organically knit grains were disaggregated, but because of their infrequent occurrence they probably do not affect the results.

Each subsample designated for petrographic analysis was separated into two fractions, sand and silt-clay.

MINERALOGY

Concentrations of carbonate minerals were determined by X-ray diffraction in both the sand and silt-clay fractions of each sample. The pulverized subsamples were placed in powder slide mounts and analyzed on a Norelco diffractometer using Cu - Kα X-radiation. A scanning rate of 1/4° per minute was used over a two-theta interval from 25.5° to 32°. The diffractometer curves were recorded on a strip chart and peak areas were measured with a planimeter.

A method of comparing peak area ratios to standard curves to obtain estimates of weight percent aragonite, low-Mg calcite, and high-Mg calcite was used. Fig. 5 presents two standard curves necessary for estimating weight percentages of desired carbonate minerals. These curves were derived from analyzing mixtures of carbonate minerals in various known proportions. Peak area ratios are plotted against weight percent carbonate minerals. Curve A was prepared from varying proportions of high-Mg calcite and aragonite. Curve B represents various combinations of high-Mg and low-Mg calcite.

Standard aragonite was derived from powdering specimens of the corals Acropora palmata and Montastrea annularis; the gastropod Cerithium sp.; and the calcified green alga Halimeda sp. A high-Mg calcite standard was derived from Homotrema rubra, the encrusting Foraminifera; the echinoid Diadema; and coralline alga, Goniolithon strictum. Reagent grade calcite was used as a low-Mg calcite standard. All specimens used for the aragonite and high-Mg calcite standards were collected from the floor of North Sound.

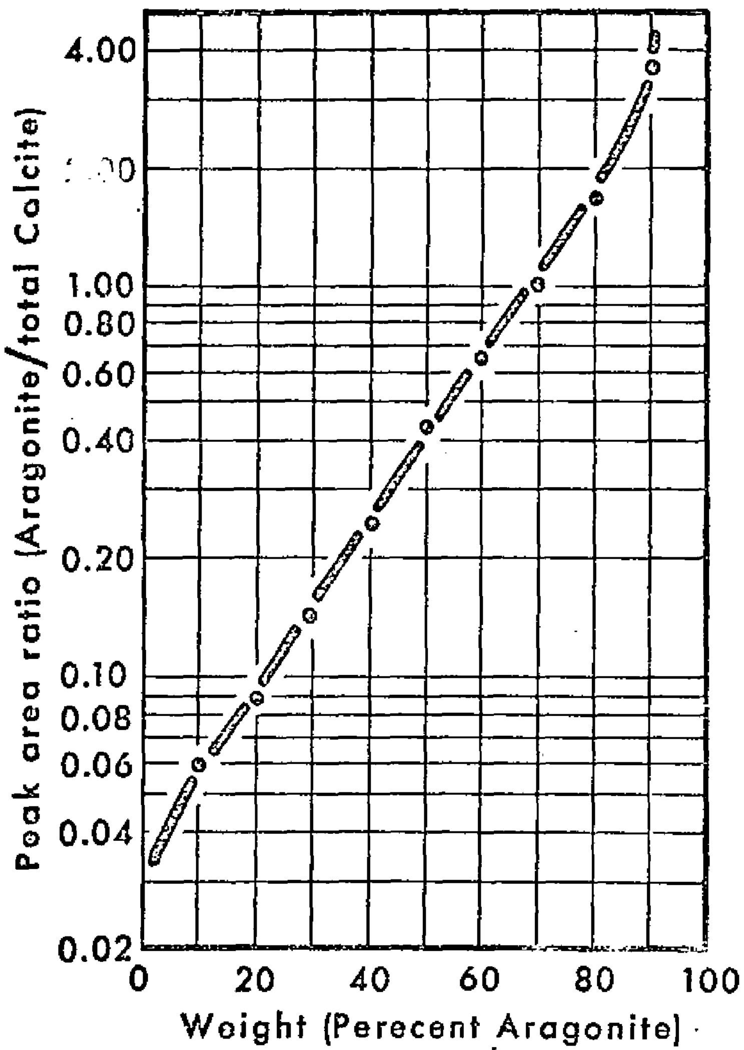


Fig. 5A. Standard curve for determination of weight percent aragonite by X-ray diffraction.

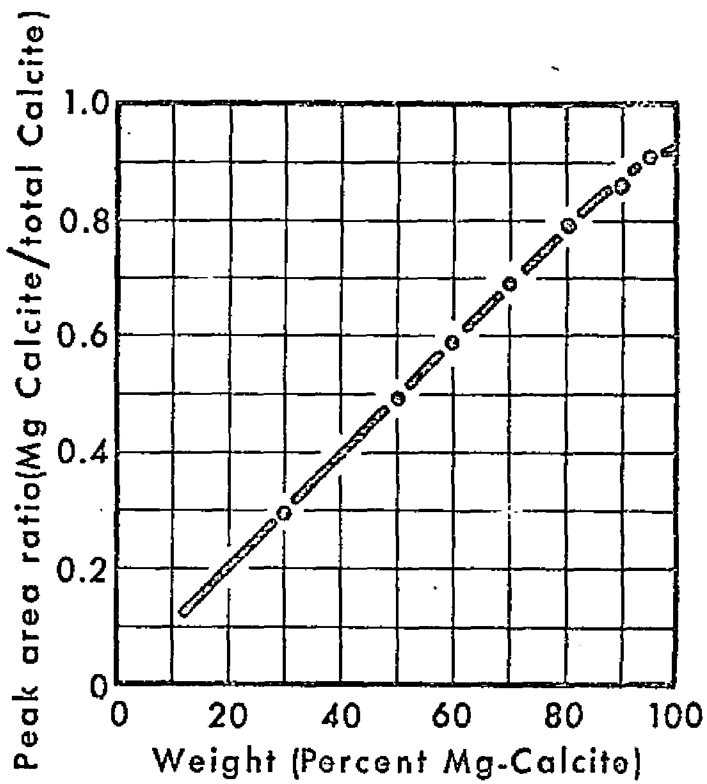


Fig. 5B. Standard curve for determination of weight percent high-Mg calcite by X-ray diffraction.

TABLE 1
ANALYTICAL PRECISION

Mineralogical data*

Mineral	Precision (%)
Aragonite	2.67
High-Mg Calcite	5.71
Low-Mg Calcite	82.36

* Precision quoted as coefficient of variation of fifteen analyses of a reef-crest sample. As Ebanks (1967) points out, concentrations of low-Mg calcite smaller than approximately 10 percent are difficult to discriminate accurately unless the high-Mg calcite is diluted by minerals. The sample tested has an average low-Mg calcite content of 2.7 percent. This accounts for the high coefficient of variation and illustrates that values of low-Mg calcite less than 10 percent should be considered very rough estimates.

The peak areas measured on diffractograms were the (111) aragonite peak at 26.2° two theta and the (104) calcite peak at 29.4° to 29.8°, depending on the amount of $MgCO_3$ in solid solution. The precision of the analysis is given in Table 1. High-Mg calcite is defined in this study as having more than 5 mol. percent $MgCO_3$. Goldsmith et al. (1955) present a discussion of the substitution of Mg in the $CaCO_3$ lattice. Their work shows that with increasing substitution of Mg ions in the calcite lattice the X-ray peak for calcite is shifted to a slightly higher two-theta position.

The shift of the calcite peak owing to magnesium substitution can best be measured if the sample contains a stable internal standard. Each sample was mixed thoroughly with powdered silicon metal in a proportion of .25 grams silicon to 2.0 grams sample. This provided an internal standard with a peak height similar to that of the carbonate minerals. From this standard peak, displacements of the calcite peak could be measured. The degree of Mg substitution and therefore the composition of Mg-calcite can be calculated by referring the position of the calcite peak to a standard curve prepared from calcite of varying known compositions. Ebanks (1967) constructed such a curve from data presented by Goldsmith _et al._ (1958).

GEOCHEMISTRY

A representative portion of each pulverized sand and silt-clay subsample was heated at approximately 150° C for 72 hours to remove organic material. The portion was then washed, centrifuged, and oven dried. Three wash and centrifuge operations for each portion were considered sufficient for the removal of ions attributable to evaporation of sea water and ashed organics.

A one-gram amount of each portion was treated with 20 ml of 1N HCl. The leach solution was then diluted to a 100 ml volume in preparation for analysis of cation concentrations with an atomic absorption spectrophotometer.

Since the samples in this study are free of terrigenous material, no error was introduced by the leaching of cation from the lattices of non-carbonate minerals. A possible source of cation addition could be from the inefficient removal of organics by the heat treatment. However, during the wash and centrifuge operation remaining organic matter was poured off as a floating residual. Comparison of results of these analyses with similar studies showed that no anomalous results were obtained. Therefore, this possible source of error may be considered minor.

TABLE 2
ANALYTICAL PRECISION

Chemical data*

Element	Precision (%)
Na	0.69
Mg	2.64
Sr	2.02

* Precision quoted as coefficient of variation on ten analyses of a reef crest sample for each element.

Analysis of the acid-leach solutions was conducted on a Perkin-Elmer model 303 atomic absorption spectrophotometer. Tests were conducted for Sr, Mg, and Na concentrations. The precision of this method is given in Table 2. Standards were prepared from reagent-grade $SrCO_3$, Mg metal, and NaCl. Stock solutions were made and appropriate dilutions prepared so that the cation ratios in the standards were near those in the unknowns.

In most spectral methods of measuring trace element content, interferences may alter results and therefore must be considered. Atomic absorption spectrometry is, however, relatively free of interferences as compared to other spectral methods. Angino and Billings (1967) point out that determination of Mg and Sr in carbonates is essentially interference-free. They also find that none of the cations or anions in normal amounts in sea water interfere with Na determinations. Therefore, interference is considered not to be a significant source of error in this study.

CONSTITUENT PARTICLE ANALYSIS

The sand-sized portion of each sediment sample was divided into coarse (-1.0 to 0.0 phi), medium (0.5 to 2.0 phi), and fine (2.5 to 4.0 phi) fractions for constituent particle analysis. A representative split of the loose sediments from each fraction was impregnated with Plaskon under a vacuum. After a curing period of 24 hours the impregnated samples were suitable for thin-sectioning. Dividing each sand sample into three parts served to (1) reduce the bias caused by differential grain settling during the impregnation process and (2) give a more accurate estimation of the constituent particle composition than that obtained by analyzing a single slide with a wide variety of sizes.

The composition of each of the three sand fractions was determined by point counting. These data were combined with the relative weights of each of the three sand fractions. A total weight percent was then applied to each constituent particle type for the entire sand sample. Ginsburg (1956) points out that point counts actually represent estimates of volume percentages.

The point count interval was set at the size of the largest grain to avoid counting the same grain twice. Each count was started at a random point from which regular traverses across the slide were made. A count of 100 grains was used on the coarse fraction because of the limited number of grains available. Two hundred grains were identified on slides of the medium and fine fractions. Estimates of point count accuracy have been shown by Ginsburg (1956), Matthews (1966), Ebanks (1967), and others to be within 10 percent of reported values.

Point counting was supplemented by staining techniques and qualitative observations of loose-grained material using a binocular microscope. Additional information was sometimes helpful in assigning problematical grains to appropriate categories.

Grain Identification

Unlike terrigenous sediments, most carbonates are partially or totally of biogenic origin. A close relationship between distinctive carbonate grain types and environment of deposition makes a petrographic analysis essential in most environmentally oriented carbonate studies. Previous studies by Ginsburg (1956), Purdy (1963), Milliman (1967), and Hoskin (1963) demonstrate the utility of thin-section analyses for rapid estimation of constituent grain percentages in sand-sized carbonate sediments.

Relative volume percentages of twelve grain types were estimated by point counts for the sand-sized sediments

(Appendix 1). Each grain falling under the cross-hairs of the microscope was tabulated in an appropriate category. Encrusted grains were tabulated as the substrate grain or the encrusting organism, depending on which fell under the cross-hairs. Voids in grains, such as chambers in a foram or gastropod test, were counted as part of the grain if completely enclosed by the remainder of the grain.

A brief description of each grain category is presented in order to clearly define each group. The most salient criteria for identifying the members of each category are pointed out. Grain types are illustrated in Plates 1 to 4.

Composite Grains

Grains assigned to this category are distinguished as having a matrix composed primarily of fine-grained carbonate with conspicuously large particles included (Plate 1). These grains range from cemented aggregates having porous interiors, the grapestones of Purdy (1963), to the well-cemented lumps of Illing (1954). No sharp division exists between one habit and another, therefore all composite grains were tabulated in a single category.

The cement binding constituent grains is of two varieties, acicular and very fine-grained. The fine-grained cement is by far the most abundant variety and appears dark gray-brown in thin section. Acicular cement is generally restricted to void fillings and contacts between constituent particles within composite grain interiors. Both cements are composed of aragonite. The constituent particles consist chiefly of mollusc, coral, coralline algae, and cryptocrystalline grains.

Undoubtedly some organic aggregates and possible fecal grains are tabulated in this category, but because of their low frequencies of occurrent no effort was made to segregate them into separate groups.

Coral

In thin section the most characteristic features of coral fragments are radial extinction, transparency, vermiform cavities usually filled with fine-grained gray-brown carbonate, and thin, dark, medial lines which represent coalescing of centers of crystallization within the septal walls. Vaughan and Wells (1943) point out that Recent scleractinid coral skeletons are composed of fine, fibrous aragonite arranged in bundles of fascicles which are stacked to form pillars (trabeculae). The fascicles or points of crystallization account for the radial extinction in coral fragments. Thin, dark, medial lines in specimens cut transversly to the septal walls result from the alignment of fiber fascicles and trabeculae and are useful in making coral fragment distinctions. The dark medial lines are caused primarily by an optical effect produced by the aggregation of minute crystals.

Coralline Algae

Rapid thin-section identification of unaltered grains of red algae is possible because of their unique and distinctive cellular internal structure. As Ebanks (1967) points out, longitudinal sections result in rectangular cell patterns, whereas cross sections tend to be polygonal. Branching, encrusting, and segmented forms of this high-Mg calcite grain type occur. In plane-polarized light grains of coralline algae have a distinctive brown color. Recrystallization appears to occur rapidly in red algae. All gradations from distinctively fresh grains to nearly featureless altered grains were noted. Combinations of crossed nicols, uncrossed nicols, and reflected light sometimes aided recognition of remnant cell structures of apparently featureless grains.

Cryptocrystalline Grains

The term cryptocrystalline as used in this paper is given no genetic significance. Grains assigned to this category are characterized by a fine-grained texture with no identifiable inclusions or structures. Commonly, these grains are light gray to tan between crossed nicols. Possible origins for such grains are discussed by Illing (1954) and Purdy (1963). Staining with Fiegel's solution suggested aragonitic composition for most of these problematical grains.

Encrusting Foraminifera

Homotrema rubra and *Planorbulina* sp. (both of which are composed of high-Mg calcite), are the two most distinctive members of this group. The presence of substrate grains on which these Foraminifera are encrusted is a prime criterion for their identification. Homotrema can readily be identified by its pink color and irregular chamber arrangement. Another distinguishing characteristic is the dark line separating a lighter inner and outer portion of the test wall. Planorbulina exhibits bulbous chambers, perforated wall structure, and a bright appearance between crossed nicols.

Miliolid Foraminifera

This group of porcelaneous Foraminifera is variably concentrated throughout the study area. Miliolids are recognized basically by their size and biloculine, triloculine, or quinqueloculine chamber arrangement. The finely textured high-Mg calcite of miliolid tests appears yellow-brown in plane polarized light and dark gray between crossed nicols in unaltered specimens. As in peneroplids, the altered tests of miliolids also seem to have undergone primarily an aggradational recrystallization process. This results in a brighter appearance between crossed nicols relative to unaltered tests.

Peneroplid Foraminifera

A separate category was erected for these large Foraminifera because of their abundance in the medium and coarse sand fractions of some samples. They are among the easiest of grain types to recognize in thin-section owing to their large size and distinctive reticulate chamber arrangement.

Viewed with plane polarized light, the tests appear light brown, but under crossed nicols the fine granular calcite composing the test walls is dark gray in an unaltered state. Altered specimens of this high-Mg calcite Foraminifera appear bright because of the interference colors of areas having undergone aggradational recrystallization.

Other Foraminifera

All Foraminifera exclusive of miliolids, peneroplids, and encrusting forms are included in this category. Most of these varieties occur in the fine sand fraction and have hyaline tests which can be composed of either low-Mg or high-Mg calcite (Blackman and Todd, 1959). Size, delicate chamber arrangement, and bright appearance between crossed nicols are the most important identifying parameters.

Halimeda

The most diagnostic feature of Halimeda grains is the network of meandering tubes, utricles, which are coarser in the center of the plate but branch into smaller tubes which intersect the surface of the plate at right angles. A perforated texture is given to the surface of the plate by this tube arrangement. The interior of a Halimeda plate exhibits numerous circular and elliptical voids which are the result of cuts through variously oriented utricles. The broad plate-like to cylindrical fragments are usually white when viewed with reflected light, but are light-to dark-brown when viewed with plane polarized light in thin section. Between crossed nicols a dark gray to brown color is characteristic of fresh specimens and probably reflects the dense fine-grained texture of the aragonite comprising the skeleton. Altered grains appear bright, light gray-brown between crossed nicols. The alteration is generally an aggradational recrystallization process. The degree of brightness between crossed nicols is directly proportional to the extent of alteration.

Molluscs

The identification of mollusc fragments is based primarily on three criteria: (1) shape, (2) skeletal microstructure, and (3) transparency. Bivalves and gastropods account for most of the fragments attributed to this category. Scaphopods were recognized, but occurred only in limited numbers. Although some Recent molluscs have shell layers of calcite, most forms have shells composed of aragonite.

Majewske (1969) presents an excellent discussion of molluscan and other skeletal microstructures which was a great aid in identification of small fragments. Large grains, even if microstructure is altered, can sometimes be identified exclusively by shape, but the smaller the fragment the more reliance must be put on shell architecture.

Algal borings are commonly associated with mollusc and coral fragments. As Purdy (1963) points out, these borings facilitate recrystallization but do not appear to cause it directly. Alteration accompanying these borings appears to be mainly by degradational recrystallization processes.

Rock Fragments

These grains consist of sand-sized particles of varying origin cemented primarily by sparry calcite. They occur mainly in areas near the shore and are fragments of the island's diagenetically altered limestone bedrock. Recognition of these grains in thin section is based primarily on the sparry low-Mg calcite cement, a characteristic yellow-brown color and indistinct structure of the constituent particles, and fragment edges which cut across particle boundaries (Plate 1).

Others

Grains not assignable to other categories were tabulated under "others." These grains fall into two general groups: (1) grains whose characteristics are confusing or insufficient for identification, and (2) skeletal grains whose frequencies of occurrence do not warrant categorization under separate headings. Skeletal grains included are echinoids, various spicule types, bryozoa, worm tubes, and *Millepora*.

PLATE 1

A. Composite grain. A variety of constituent grain types have been cemented into an aggregate grain with a porous interior. Two cement types are present: (a) a clear acicular variety concentrated in the grain interior, and (b) a fine-grained variety restricted to the peripheral areas of the grain. Crossed nicols (x26).

B. Coral grain. The septa and their thin, dark, medial lines (a) are especially distinctive in this coral fragment. Crossed nicols (x26).

C. Encrusting coralline algae. The reticulate cell structure and opaqueness of the coralline algae contrasts highly with the relatively transparent coral grains on which it is encrusting. Plane polarized light (x42).

D. Articulate red algae. Note the unaltered cellular structure. Plane polarized light (x26).

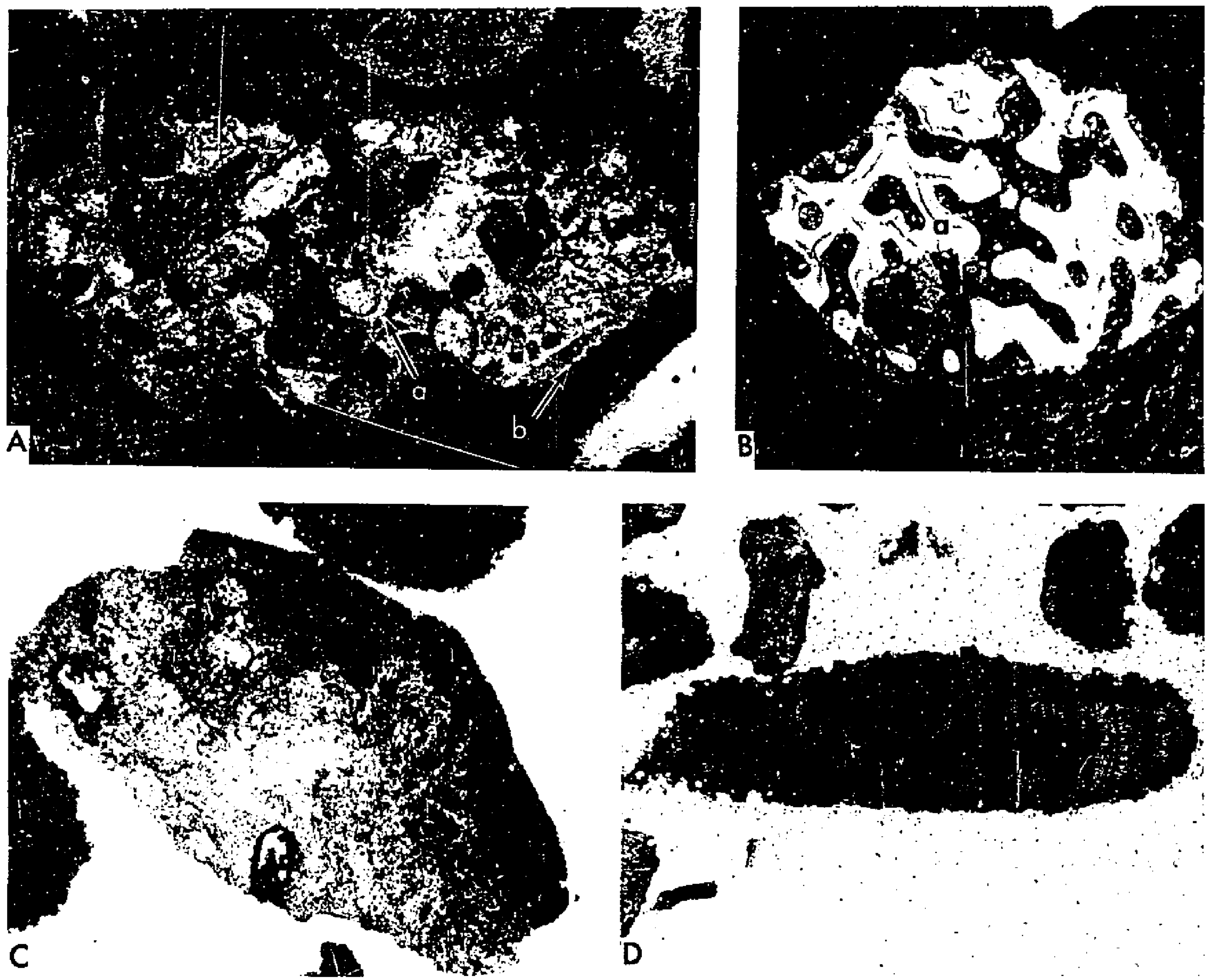

A
a
b
B
a
C
D

PLATE 2

A. Cryptocrystalline grain. Note the fine-grained texture and structureless form of the grain. Crossed nicols (x45).

B. Encrusting foraminifer. Bulbous chambers with transparent, perforate test walls are characteristic of this planorbid foraminifer. Plane polarized light (x26).

C. Encrusting foraminifer, _Homotrema rubra_. Photograph shows the irregular cellular pattern of this foraminifer and its mollusc substrate grain. In plane light _Homotrema rubra_ has a pink hue. Plane polarized light (x26).

D. Miliolid foraminifer tests. Two miliolids are shown: (a) a biloculine form, and (b) a quinqueloculine variety. Plane polarized light (x42).

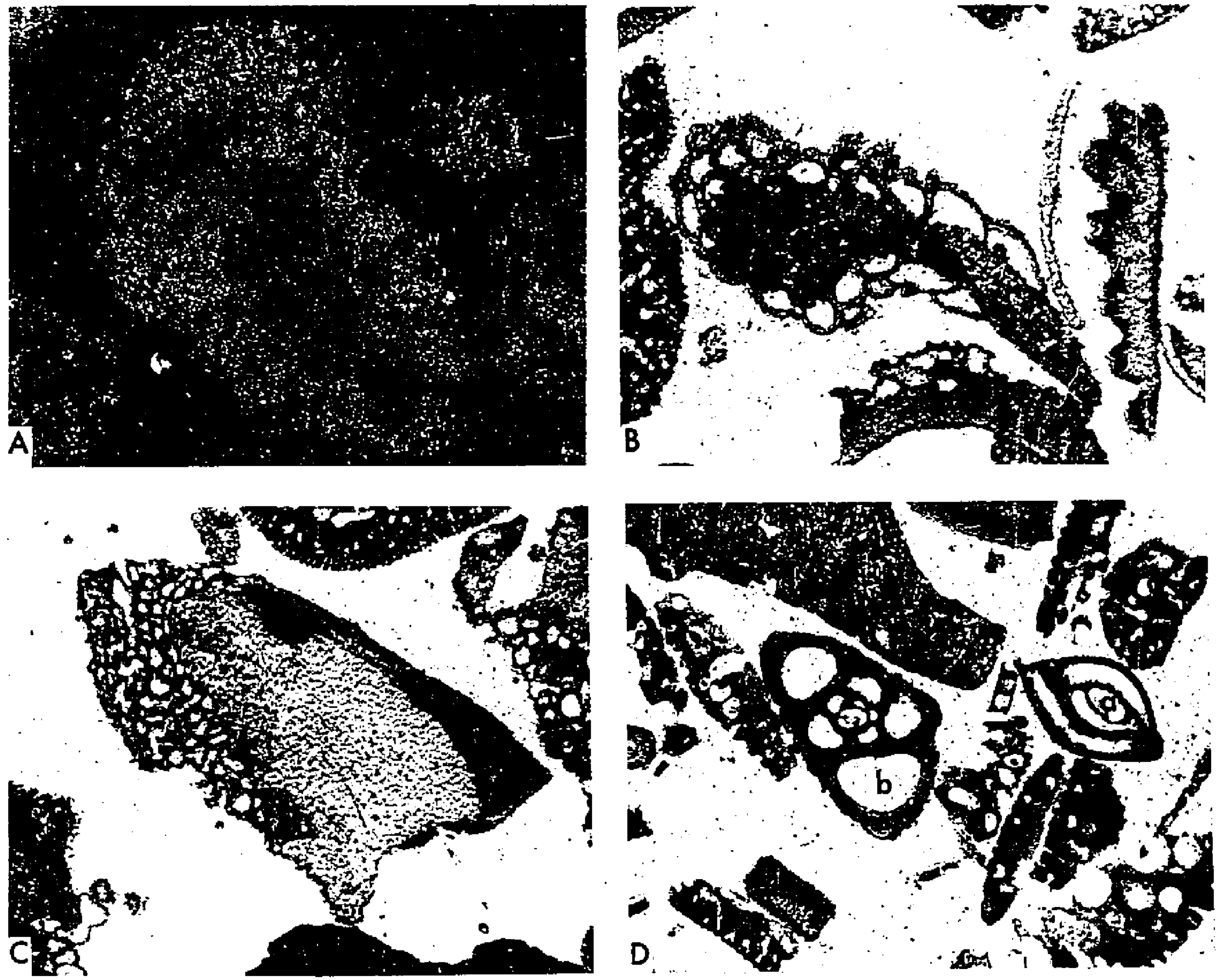

A
B
C
D
b

PLATE 3

A. Peneroplid foraminifer test. The unaltered test shows a distinctive reticulate chamber arrangement. Plane polarized light (x42).

B. _Halimeda_ grain. The extensive network of meandering tubes gives _Halimeda_ grains a characteristic perforated appearance. Crossed nicols (x26).

C. Mollusc grain. This grain shows a distinct skeletal microstructure and "bright", transparent appearance. Crossed nicols (x26).

D. Rock fragment grain. Note the ellipsoidal shape of the rock fragment and the well cemented arrangement of its constituent grains. Edges of the rock fragment cut across the boundaries of a constituent grain (a). A large _Halimeda_ grain shows extensive pore filling and truncated boundaries (b). Crossed nicols (x26).

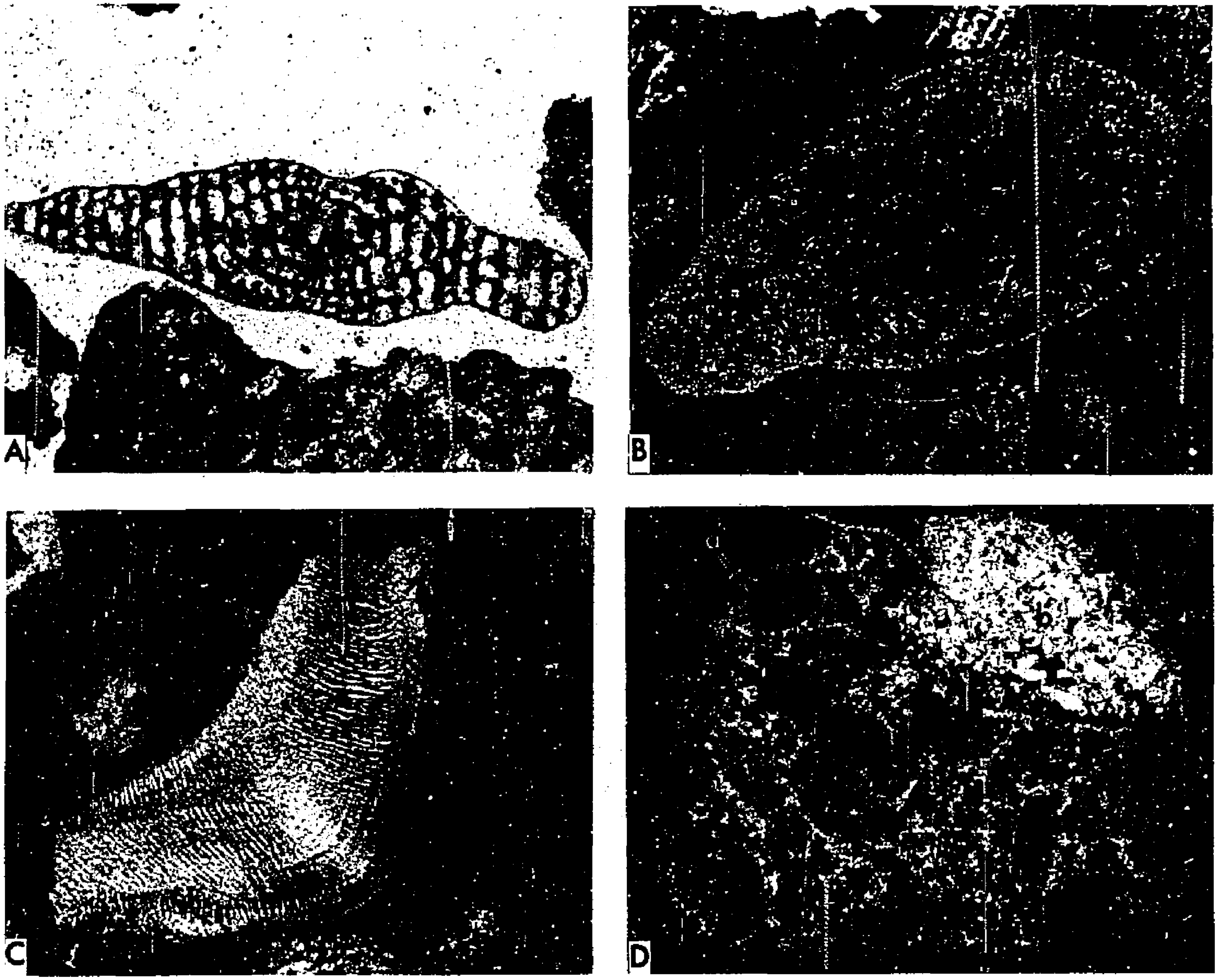
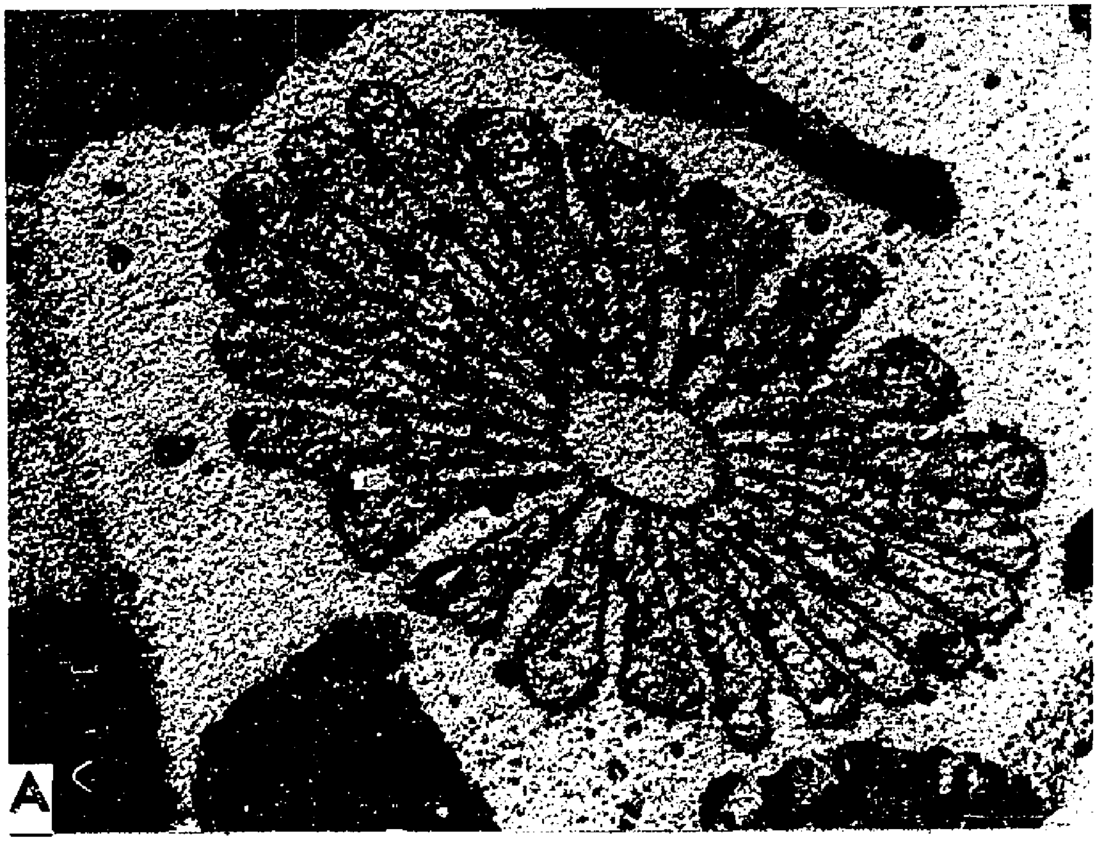

A
B
C
D

PLATE 4

A. Spicule grain. Plane polarized light (x72).

B. Oblique section through an echinoid spine. Plane polarized light (x36).


A


B

RESULTS OF ANALYSES

INTRODUCTION

Data collected for investigation of variation between the major environments of North Sound are presented in separate sections devoted to each aspect of the study: ecology, constituent particle analysis, mineralogy, and chemistry. Raw data for each sample--point counts, mineral percentages, and acid-leach cation concentrations--are tabulated in the Appendices.

The basin of deposition was divided into four environments for comparison of quantitative data: reef-shoal, shore zone, grass plain, and restricted lagoon. Although the reef-shoal environment can be subdivided into areas with distinct sediment-producing organic communities, its sediments were studied as a unit. High energy conditions near the reef generally mix and transport sediments in a lagoonward direction. Therefore, the sediments of the reef-shoal exhibit the summation of characteristics of all environments near the reef. Quantitative data were collected on compositional, mineralogical, and chemical parameters. Qualitative information was collected on the types and distribution of sediment-producing organisms living throughout the depositional basin.

ECOLOGY

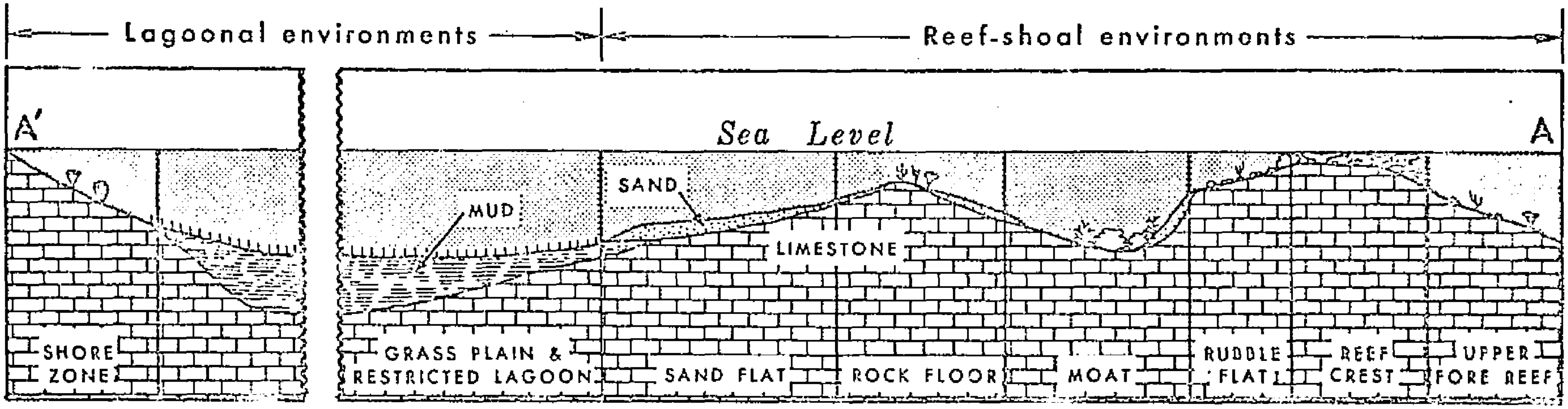
The close relationship between carbonate sediments and organisms living in the basin of deposition make it informative to characterize a study area in terms of its biologic communities. Carbonate sediments in many places are composed partly or entirely of skeletal debris from marine plants and animals. The identification and distribution of these sediment-producers is important. Ginsburg et al. (1963) points out that the distribution of organisms on the sea floor is not determined by chance, but varies systematically with changes in environmental conditions. North Sound is no exception to the rule.

North Sound may be divided into two major areas on the basis of energy conditions and submarine topography: (1) reef-shoal and (2) lagoon. The reef-shoal is characterized by relatively shallow water, high energy conditions, and coarse-grained sediments, whereas slightly deeper water and lime muds are associated with the quiescent conditions of the lagoon. Within these major areas there are definite groupings of organic communities. A cursory observation of the benthonic plants and animals from the reef to the lagoon interior is in itself convincing evidence that a marked development of associations between benthonic organisms exists. Although many factors - physical, chemical, and biological - help control the distribution of marine organisms, submarine topography and substrate were found to be most suitable criteria for delineation of sub-environments and their organic communites. The following sub-environments were recognized and used as a reference for describing the benthonic communities of the study area: reef crest, rubble flat, moat, exposed rock floor, sand flat, grass plain, restricted lagoon, and shore zone. Fig. 6 is a schematic profile from the upper fore reef to the southern shoreline of North Sound. Table 3 summarizes the dominant faunal and floral members of each environmental subdivision and Plates 5 and 6 show their appearance in the field.

Reef Crest

The fringing reef which separates North Sound from the open sea is a submarine ridge intermittently broken by channels. At low tide the highest points on this ridge are exposed. Its rather flat crest is colonized by a flourishing growth of corals and more subordinate forms of benthonic marine life (Fig. 6). It is the culmination of two oppositely sloping surfaces, a seaward dipping rock surface in the fore reef and a shoreward dipping debris plane in the back reef. Although all the fringing reefs of Grand Cayman exhibit very similar submarine topography, the reefs of North Sound support the most luxuriant reef crest coral community.

The most abundant and structurally the most important coral at the reef crest is the large, branching *Acropora palmata*. It clearly is the dominant form of marine life in the reef crest community. A preferential orientation of the tree-like colonies occurs with fronds extended toward prevailing seas. More symmetrical, flower-like colonies occur in the more protected shoreward areas of the reef crest.



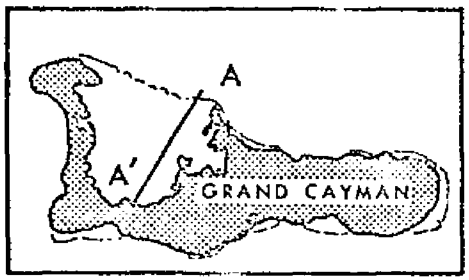


Fig. 6. Schematic north-south cross section of North Sound.

TABLE 3

ORGANISMS COMMON TO THE VARIOUS ENVIRONMENTS OF NORTH SOUND

ORGANISMS*	LAGOON ENVIRONMENTS			REEF-SHOAL ENVIRONMENTS				
	SHORE ZONE	RESTRICTED LAGOON	GRASS PLAIN	SAND FLAT	ROCK FLOOR	MOAT	RUBBLE FLAT	REEF CREST
GREEN ALGAE	Acetabularia sp. Avrainvillea sp. Caulerpa sp. Dasycladus sp. Halimeda sp. Padina sp. Penicillus sp. Rhipocephalus sp. Udotea sp.	Acetabularia sp. Avrainvillea sp. Halimeda sp. Penicillus sp. Rhipocephalus sp. Udotea sp.	Acetabularia sp. Avrainvillea sp. Halimeda sp. Penicillus sp. Rhipocephalus sp. Udotea sp.	Acetabularia sp. Caulerpa sp. Halimeda sp. Penicillus sp. Rhipocephalus sp. Udotea sp.	Halimeda sp.	Halimeda sp. Penicillus sr	Halimeda sp.	Halimeda sp.
FORAMINIFERA	Miliolids Peneroplids	Miliolids Peneroplids	Miliolids Peneroplids	Miliolids Peneroplids			Homotrema rubra	Homotrema rubra
BIVALVES	Pecten sp.	Chione sp. Codakia sp. Diplodonta sp. Glycymeris sp. Laevicardium sp. Pecten sp. Pinna sp.	Chione sp. Codakia sp. Diplodonta sp. Glycymeris sp. Laevicardium sp. Pecten sp. Pinna sp.	Glycymeris sp. Pecten sp. Tellina sp.	Boring clams	Boring clams	Boring clams	Boring clams
GASTROPODS	Astraea sp. Cerithium sp. Cyphoma gibbosum Littorina sp. Strombus gigas	Astraea sp. Cerithium sp. Littorina sp.	Astraea sp. Cerithium sp. Cyphoma gibbosum Littorina sp. Strombus gigas	Strombus gigas				
CORALS	Porites astreoides Porites divaricata Porites furcata Siderastrea radians	Porites divaricata	Porites divaricata	Acropora cervicornis	Diploria clivosa Porites astreoides Siderastrea radians	Acropora cervicornis Agaricia agaricites Agaricia nobilis Diploria labyrinthiformis Diploria strigosa Montastrea annularia	Diploria clivosa Porites astreoides Siderastrea radians Siderastrea siderea	Acropora palmata Agaricia agaricites Agaricia nobilis Diploria clivosa Diploria strigosa Montastrea annularis Porites astreoides Porites porites Siderastrea siderea
MILLEPORA	Millepora alcicornis						Millepora alcicornis	Millepora alcicornis
CORALLINE ALGAE	Goniolithon sp.				Encrusting lithothamnid forms		Encrusting lithothamnid forms	Encrusting lithothamnid forms
ECHINOIDS	Diadema sp. (Long spine)		Short spine varieties	Short spine varieties	Diadema sp. (Long spine)		Diadema sp. (Long spine)	Diadema sp. (Long spine)
SPONGES	Cliona sp. Loggerhead	Grass encrusting varieties	Cliona sp. Loggerhead	Cliona sp.	Cliona sp.		Cliona sp.	Cliona sp.
BROWN ALGAE	Padina sp. Turbinaria sp.				Padina sp.		Padina sp. Zonaria sp.	
WORMS		Arenicola ? Mound-building polychaetes	Arenicola ? Mound-building polychaetes	Arenicola ? Mound-building polychaetes	Serpulids	Serpulids	Serpulids	Serpulids
GRASS	Thalassia testudium	Thalassia testudium	Thalassia testudium	Thalassia testudium				
OTHERS	Alcyonarians Bryozoa Holothurians Starfish	Holothurians Scaphopoda	Holothurians Scaphopoda Starfish	Bryozoa Scaphopoda Starfish	Alcyonarians		Alcyonarians Bryozoa	Alcyonarians Bryozoa

* Organisms listed in order of importance as sediment-producers (most important at top).

PLATE 5

A. Reef crest. _Acropora palmata_ (a) is the most prolific coral of the reef crest environment. Bladed _Millepora alciconis_ (b) and alcyonarians (c) are also present.

B. Rubble flat. A tossed colony of _Acropora palmata_ (a) was broken from the reef crest and transported lagoonward to the rubble flat.

C. Moat. Patch reefs of _Montastrea annularis_ (a) are common in the moat environment. Coral debris (b) marks the interface between the moat and rubble flat.

D. Moat. _Acropora cervicornis_ (a), _Montastrea annularis_ (b), and alcyonarians (c) are common members of the moat fauna.

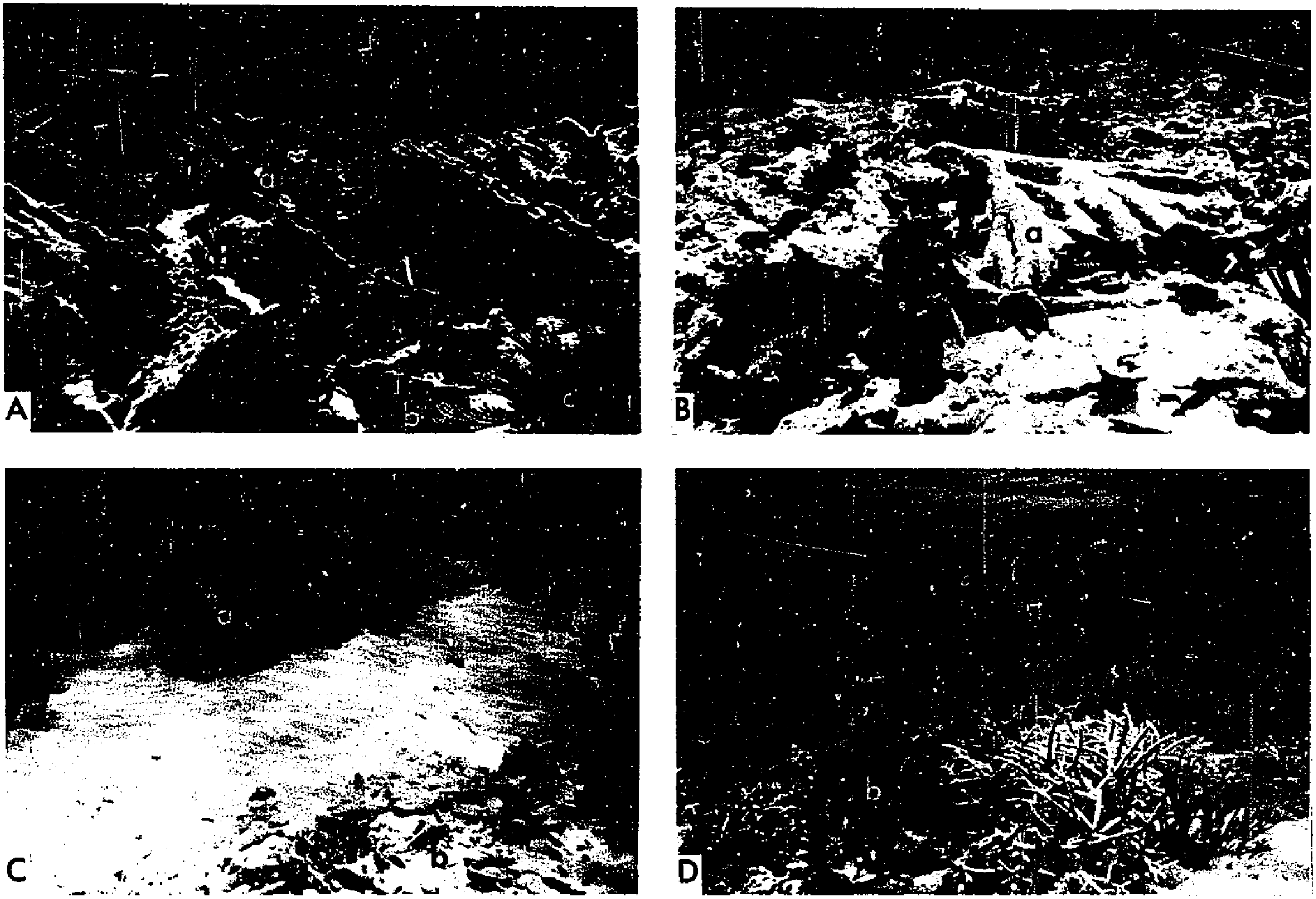

A
B
C
D

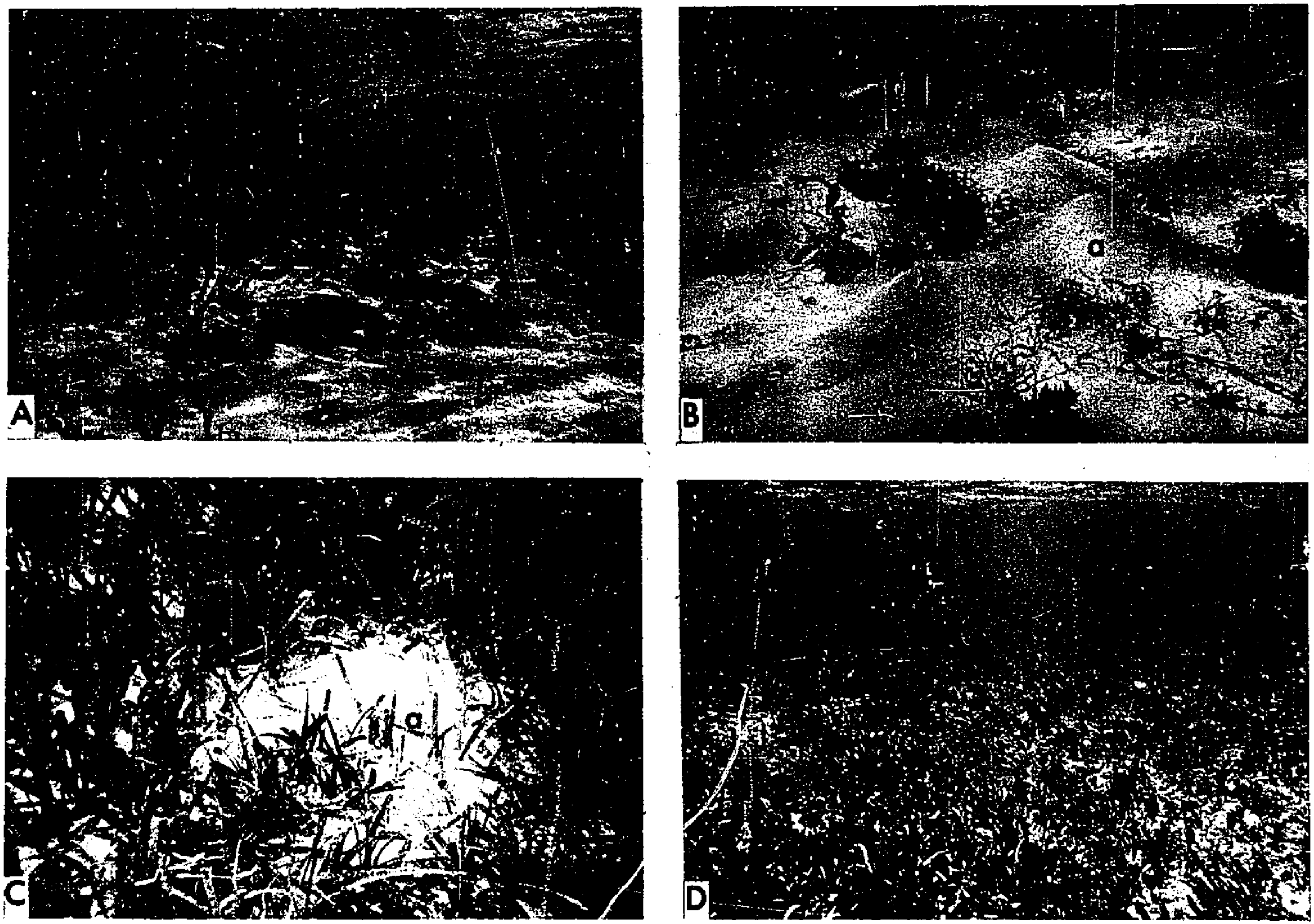
PLATE 6

A. Rock floor. A rock ridge is shown protruding through the sediment cover. These rock floor areas are usually colonized by alcyonarians (a) and small heads of coral (b).

B. Sand flat. Numerous worm mounds (a) and sparse grass growth (b) are characteristic of this environment.

C. Grass plain. Thick *Thalassia* growth with numerous intermittent worm mounds (a) characterize the grass plain. A *Pinna* in growth position (b) and an echinoid shell (c) are shown.

D. Shore zone. *Thalassia* and many varieties of calcareous green algae inhabit this environment.


A
B
a
C
a
D

The fronds and trunks of these colonies are thin, whereas those taking the full force of the surf tend to be more massive. A. palmata gives the area an irregular comb-like appearance with teeth extended seaward.

Other corals occur at the reef crest, but are distinctly less abundant than A. palmata. Heads of Diploria strigosa, D. clivosa, and Montastrea annularis up to several feet in diameter are common between the colonies of A. palmata. These subordinate corals can be found throughout the reef crest, but appear to be more concentrated shoreward of the greatest concentration of A. palmata. Smaller corals, Agaricia agaricites, A. nobilis, Porites porites, and P. astreoides, find suitable ecologic niches under and between the larger corals.

The hydrozoan Millepora alcicornis occurs both in bladed and encrusting forms. Like A. palmata it can withstand a very high energy environment. In areas where A. palmata is missing from the reef crest community, probably destroyed by storms, bladed M. alcicornis becomes very abundant. Encrusting M. alcicornis usually occurs on alcyonarians.

Halimeda is rather inconspicuous but is present at the reef crest. An abundance of the long-spine echinoid Diadema sp., along with many other small varieties of benthonic life, occur in ecologic niches provided by the larger and more noteworthy members of the environment.

Encrusting Foraminifera, especially Homotrema rubra, and coralline algae cover the bases of coral colonies and debris trapped in the structural framework of the reef. Algal coatings are not restricted to the reef crest, but extend shoreward on a rubble-covered plane built by wave-tossed debris from the reef crest.

Rubble Flat

Topographically, the rubble flat slopes very gently shoreward from the reef crest and is covered by shallow water over its entire extent (Fig. 6). It is formed almost exclusively of boulder- and cobble-sized pieces of Acropora palmata, extensively bored and encrusted by marine organisms. However, when compared to the lush coral fauna of the reef crest this environment appears very sparsely populated.

Encrusting organisms include calcareous red algae, the Foraminifera Homotrema rubra, serpulids, Bryozoa, Millepora alciocornis, and others. Small clumps of Padina and other brown algae are common. The abundance of these algae gives the rubble flat an over-all brown appearance. Green algae are present, but in limited varieties and numbers.

Alcyonarians, bladed M. alcicornis, and a few scattered coral heads comprise the largest faunal elements. The most common corals on the rubble flat are Diploria clivosa, Porites astreoides, Siderastrea radians, and S. siderea.

As an accessory organism the long-spined echinoid, Diadema sp., is very abundant among the coarse debris of the rubble flat.

Moat

At the shoreward limit of the rubble flat, sand progressively replaces boulders and cobbles. The bottom profile at this point drops rather abruptly, forming a channel-like feature. This depression parallels the reef trend and gradually shallows shoreward (Fig. 6). The width of the moat zone is variable, and water depths range from approximately 6 to 15 feet. The bottom is either a current-swept rock surface or a thin veneer of sand, usually ripple marked. Algae-encrusted coral rubble derived from collapsed colonies of *Acropora cervicornis* is present in localized areas. The density of living coral appears to vary inversely with the occurrence of sand on the bottom.

The moat community can be characterized by *Montastrea annularis*, *A. cervicornis*, and alcyonarians. Hemispherical and donut-shaped heads of *M. annularis* up to approximately 10 feet in diameter form the nucleus for patch reefs. Smaller and less important corals associated with these large heads include *Agaricia agaricites*, *A. nobilis*, *Dendrogyra cylindrus*, *Diploria labyrinthiformis*, *D. strigosa*, *Eusmilia fastigiata*, *Porites asteroides*, *P. furcata*, *P. porites*, and *Siderastrea siderea*. Alcyonarians and colonies of delicately branching *A. cervicornis* inhabit areas between patch reefs. Locally, *A. cervicornis* is concentrated into thickets and its greatest density is shoreward of that of *M. annularis*.

A sparse growth of green algae covers the stabilized sand areas among the patch reefs, coral thickets, and on the sandy shoreward flank of the moat. *Halimeda* is the most common green alga associated with the corals. *Penicillus* joins *Halimeda* in being the most abundant calcareous green alga in the stabilized sand areas.

Rock Floor

Between the moat and the lime muds of North Sound's interior is a band of exposed rock floor which parallels the present day fringing reef (Fig. 6). This relatively sediment-free area is topographically higher than adjacent areas. It forms a slight barrier between the living reef and the interior of North Sound.

The organic community colonizing this submarine ridge is typical of most exposed, rocky substrates. Alcyonarians and a spectrum of brown algae are most characteristic. An impoverished scleractinian fauna consisting mainly of *Diploria clivosa* and *Siderastrea radians* is present. *Millepora alcicornis* is present, but usually is limited to finger-like encrustations of alcyonarians. Other encrusting organisms relatively common to the rocky floor are coralline algae and the yellow-brown boring sponge, *Cliona*. Black, long-spined echinoids, *Diadema*, are especially numerous in the irregular rocky areas. Where sand thinly veneers the rock floor a sparse growth of green algae, marine grasses, and loggerhead sponges results.

Sand Flat

Shoreward of the rock floor belt is a sizeable concentration of sand in the northern and northeastern areas of the sound. This rather stable sand is spread in a continuous apron across much of the northern portion of the sound (Fig. 6).

Green algae are the most predominant members of the sand flat community. _Penicillus_ and _Halimeda_ account for the bulk of green algae present. _Rhipocephalus_, _Udotea_, and _Acetabularia_ are less populous forms. A sparse growth of turtle grass, _Thallassia testudium_, is interspersed with the green algae. The large gastropod _Strombus gigas_ is present throughout the sand flat and starfish are rather abundant in localized areas.

Conical mounds of sand constructed by marine organisms, possibly the worm _Arenicola_, are common on the sand flat and continue to occur as the sand apron grades into the grassy meadows of North Sound's interior.

Grass Plain

This subdivision of the broad lagoonal environment accounts for apprximately 60 percent of the total area of North Sound. Most of the hummocky, worm-mounded bottom supports a lush growth of marine grass, _Thalassia testudium_, and an abundance of calcareous green algae. Marine grass forms a stabilizing cover for the relatively thick accumulation of sediments. Green algae are second in abundance to marine grass. Various species of the genera _Halimeda_, _Penicillus_, _Rhipocephalus_ were the most frequently observed varieties. Other forms, _Acetabularia_ and _Avrainvillea_, are less abundant and tend to concentrate in localized areas. Although some areas appear to have a sparse calcareous green algae population, Stockman, Ginsburg, and Shinn (1967) point out that their life cycles are so short that a small population is capable of producing a significant quantity of fine-grained sediment.

Holothurians, short-spined echinoids, various gastropods, and the unattached coral _Porites divaricata_ find the grass plain a suitable habitat (Table 3). The grass functions as a substrate for small encrusting sponges, Bryozoa, and Foraminifera. Judging from the bivalves scattered over the bottom, a rather abundant infauna must reside in the soft muds. _Chione_, _Codakia_, _Glycymeris_, _Laevicardium_, and _Pinna_ are the most abundant genera.

Benthonic Foraminifera contribute significantly to the sediments of the grass plain. Miliolids and peneroplids are the most numerous; however, a rather large spectrum of genera is present. A list of frequently occurring forms is presented in Appendix 4.

Grass of the lagoon thins to the north, where lime muds of the grass merge with sands of the reef-shoal environment. The western and southern boundaries of the grass plain are transitional with a narrow shore zone which offers little sediment in which the grass may take root.

Shore Zone

Along the western and southern margins of North Sound there exists a zone several hundred yards wide in which the sediment cover is reduced to a thin veneer over the lagoon's limestone floor. Organisms preferring solid substrates have colonized this area and offer a marked contrast to the communities of the grass plain. Alcyonarians, loggerhead sponges, and small coral colonies - *Porites divaricata*, *P. furcata*, and *Siderastrea radians* - are common members of the organic community. The calcareous red algae *Goniolithon strictum* is concentrated locally.

A wide variety of brown and green algae cover the bottom. The brown algae, of which *Padina* and *Turbinaria* are very common, are relatively restricted to the rocky floor areas. Calcareous green algae are also abundant throughout the shore zone. In areas where the sediment cover thickens, forms anchored in the sediment by basal masses of rhizoids increase in abundance. *Halimeda*, *Penicillus*, *Rhipocephalus*, and *Udotea* are algae of this variety. Other green algae are present and abundant in the shore zone (Table 3).

Burrowing bivalves are limited in the shore zone as a consequence of the shallow sediment cover. Gastropods, Foraminifera, and others exhibit similar occurrences both in kind and number to those on the grass plain.

Restricted Lagoon

Little Sound constitutes a restricted area of the lagoon environment (Fig. 4). It is a natural division in the sedimentary basin because of its isolation from the main current patterns in the major portion of the lagoon, its slightly different organic community, and its highly organic fine-grained sediments.

The marine grass *Thalassia testudium* is the most characteristic member of the restricted lagoon's organic community. As in the grass plain, the bottom is dotted with sediment mounds formed by burrowing marine organisms. Calcareous green algae and other organisms typically found in the grass plain can usually be noted in the restricted lagoon.

CONSTITUENT PARTICLE ANALYSIS

Relative percentages of constituent grain types were derived from thin section point counts of sand size particles. Initially, twelve constituent grain categories for tabulation of point count data. The relative percentage of each category for the sand fraction of every sample is listed in Appendix 1. Most Foraminifera common to Grand Cayman sediments are composed of high-Mg calcite, 10-15 mole % $MgCO_3$. Therefore, all Foraminifera were combined into a single category for statistical comparisons. Nine major groupings resulted for statistical treatment.

Data were arranged in a completely randomized design analysis of variance model, Steele and Torrie (1960). This procedure was used to derive summary statistics for and to assess the significance of differences between grain categories and four major environmental subdivisions in the basin of deposition. A matrix of means associated with the analysis is presented in Table 4. Mean squares and the results of F-tests which evaluate the differences among environment means are tabulated in Table 5.

The analysis indicates differences between mean concentrations of eight of nine variables were significantly greater between environments than can be attributed to random variation. All tests were significant at the .01 level of significance. To determine where these differences arise, environment means for each variable are inspected. These data are presented in Table 4.

TABLE 4

ANALYSIS OF VARIANCE MEANS FOR CONSTITUENT PARTICLES*

	GRAIN CATEGORIES								
ENVIRONMENTS	1	2	3	4	5	6	7	8	9
Reef-Shoal	3.2	19.8	10.1	9.7	10.7	22.5	16.2	0.1	3.5
Shore Zone	0.5	0.5	0.4	11.1	14.5	42.5	16.2	6.6	3.6
Grass Plain	0.2	0.1	0.5	4.8	22.0	56.4	11.5	0.1	2.4
Restricted Lagoon	0.3	0.1	0.8	6.2	14.1	48.8	22.6	0.4	3.4

* Means are tabulated as percentages transformed from arcsin values.

** Grain Categories: 1 Composite Grains; 2 Coral; 3 Coralline Algae; 4 Cryptocrystalline; 5 Foraminifera; 6 <u>Halimeda</u>; 7 Molluscs; 8 Rock Fragments; 9 Others

Composite grains have relatively low frequencies of occurrence throughout the study area, however the highest concentration occurs in the reef-shoal environment. This grain category encompasses a spectrum of aggregate grain types. All composite grains ranging from organic aggregates to grapestones are included. The greatest concentrations are found in localized areas lagoonward of breaks in the fringing reef across North Sound. Through openings in the reef oceanic waters interact with lagoonal waters. Precipitation of fine grain and acicular aragonite serves to cement constituent particles into aggregate grains.

Coral is plentiful in reef-shoal sediments, but relatively absent from sediments in other environments of North Sound. Inspection of the means in Table 4 shows that although approximately one-fifth of the reef-shoal sands are composed of coral, this grain type is practically nonexistent in sediments of other environments. A highly significant F-ratio results when the coral content of sediments from all environments is compared, Table 5.

Cryptocrystalline grains exhibit significant differences in mean concentration between environments. Reef-shoal and shore zone sediments have similar and relatively high concentrations of this grain type, whereas the grass plain and restricted lagoon are somewhat lower. Different genetic significance is implied by the occurrence of this problematical grain category. Illing (1954), Purdy (1963), and others have recognized the probable multiple origins for these grains. Cryptocrystalline grains in the sediments of North Sound could have been tabulated from the following sources: (1) diagenetically altered grains eroded from rock fragments derived either from the floor of the sound or adjacent limestone outcrops, (2) grains altered to cryptocrystalline calcite

TABLE 5

ANALYSIS OF VARIANCE OF CONSTITUENT PARTICLES

SOURCE OF VARIATION	df	GRAIN CATEGORIES*									EMS
		1	2	3	4	5	6	7	8	9	
Environments	3	217.2	2304.5	833.5	197.5	311.8	1497.1	141.8	592.6	18.1	$\sigma_E^2 + 13.8$
Error	60	33.1	53.8	29.7	26.2	32.3	98.6	14.1	16.1	7.9	σ_E^2
Total	63										
F - Ratios		6.6**	42.8**	28.1**	7.5**	9.7**	15.2**	10.1**	36.8**	2.3	

* Grain Categories:
1 Composite Grains
2 Coral
3 Coralline Algae
4 Cryptocrystalline
5 Foraminifera
6 *Halimeda*
7 Molluscs
8 Rock Fragments
9 Others

** F - ratio significant at the .01 level.

by recent diagenesis, and (3) particles in the fine grain sizes which have lost their identifying characteristics and therefore must be tabulated as cryptocrystalline.

A significant difference in Foraminifera content between environments results primarily from a relatively high concentration in the grass plain. Table 4 shows a considerable difference exists between the reef-shoal environment and means from the three lagoonal environments. Peneroplids and miliolids account for most of the lagoonal Foraminifera (Appendix 1). These two types of Foraminifera are most concentrated in the quiet water sediments of the grass plain. The encrusting variety, Homotrema, is common in the high energy reef-shoal environment. Active wave and current conditions of the reef-shoal are not conducive to unattached benthonic Foraminifera.

Halimeda occurs ubiquitously throughout North Sound. Although it is produced and deposited in the reef-shoal environment, means in Table 4 show significantly higher concentrations in lagoonal environments. The shore zone, grass plain, and restricted lagoon exhibit means of approximately the same magnitude. Therefore, the major variation arises from a decrease in relative percentage of Halimeda occurring in reef-shoal sediments. Approximately half of grass plain sand-size sediments are composed of Halimeda as compared to approximately one-fifth in reef-shoal sediments.

The analysis indicates that differences between environments with respect to mollusc fragments result mainly from a large mean concentration in the restricted lagoon. Table 4 shows that nearly one-fourth of the total sand composition in the restricted lagoon can be attributed to mollusc debris. The remaining three environments of North Sound exhibit considerably less mollusc matter in the sand fraction. The quiet water and organic sediments of the restricted lagoon appear most favorable for a large molluscan population. A relative increase of molluscan fragments in restricted lagoon sediments is at the expense of reductions in Foraminifera and Halimeda.

Rock fragments are highly variable grain types between environments. Inspection of environment means in Table 4 shows the shore zone is the only environment whose sand size sediments contain an appreciable quantity of these grains. There are two possible origins for rock fragments: (1) eorsion from the limestone country rock bordering the shore zone and (2) erosion of the limestone floor of the sound.

No significant differences were found between environments with respect to the "others" category.

SEDIMENT MINERALOGY

The sediments of North Sound are complex mixtures of primarily skeletal debris from a variety of sediment-producing organisms. The mineralogy of these and most recent carbonate skeletons can be divided into three phases: calcite, aragonite, and a spectrum of Mg calcites. A single sediment sample has mineralogical and chemical properties which are therefore the mean result of the properties of various biogenically derived components. Each component has compositional characteristics governed by the life processes of the sediment-producing organisms from which it was derived.

Total variation in carbonate mineral and acid-leach cation concentrations was partitioned with respect to environment and size fractions. A least-squares procedure as outlined by Harvey (1960) was used. This approach corrects for an unbalanced sampling design. Concerning the present study this applies to samples in which either the sand or silt-clay fraction could not be analyzed. In most cases, samples from areas near the reef had little or no measurable silt-clay content. Output from the least-squares program included weighted mean values for environments, size fractions, interactions between classes of these two factors and standard analysis of variance summaries.

The results of analysis of mineralogical data are presented in two tables. Table 6 contains the matrix of adjusted main effects and interactions, and Table 7 presents analysis of variance summaries plus the results of F-tests which evaluate the significance of differences between the main effects and interactions.

Carbonate mineral percentages were calculated as though the sediments were composed of pure calcium carbonate. Small amounts of biogenic silica appear to be the only other mineral phase present. Silica accounts for much less than one percent of the total sediment.

TABLE 6

MATRIX OF ADJUSTED MEANS AND MAIN EFFECTS FOR MINERALOGY
(PERCENTAGES)

VARIABLE		ENV. 1*	ENV. 2*	ENV. 3*	ENV. 4*	SAND	SILT-CLAY
Aragonite	Environment	59.7	52.6	53.7	60.2		
	Sand	72.1	61.6	63.3	70.5		
	Silt-Clay	46.7	43.6	43.9	49.5		
	Size Fraction					66.9	45.8
High-Mg Calcite	Environment	33.9	32.6	42.0	31.8		
	Sand	24.8	20.3	32.9	21.2		
	Silt-Clay	43.7	46.2	51.4	43.2		
	Size Fraction					24.7	46.2
Low-Mg Calcite	Environment	4.8	13.1	2.8	6.7		
	Sand	2.4	16.7	2.6	6.6		
	Silt-Clay	7.9	9.8	3.1	6.8		
	Size Fraction					6.1	6.6

* Environments: 1. Reef-Shoal, 2. Shore Zone, 3. Grass Plain, 4. Restricted Lagoon.

TABLE 7

ANALYSIS OF VARIANCE SUMMARY OF MINERALOGY

SOURCE OF VARIATION	df	Aragonite Mean Square	Aragonite F-Ratio	High-Mg Calcite Mean Square	High-Mg Calcite F-Ratio	Low-Mg Calcite Mean Square	Low-Mg Calcite F-Ratio
Environments	3	131.3	4.1**	306.5	7.8**	732.6	16.0**
Size Fractions	1	3100.0	96.4**	3474.7	88.3**	7.0	0.2
Interactions	3	31.4	0.9	38.3	0.9	187.0	4.1**
Error	121	32.2		39.4		45.8	
Total	128						

** Significant at the .01 level of confidence.

The analysis shows that differences in mean aragonite and high-Mg calcite between environments and between sediment fractions are significantly greater than would be expected by chance alone. Inspection of environment and fraction means (Table 6) shows that the shore zone has the smallest mean concentration of aragonite, and reef-shoal and restricted lagoon sediments have the highest. The grass plain exhibits the greatest mean concentration of high-Mg calcite as opposed to the restricted lagoon, which has the lowest.

With respect to both high-Mg calcite and aragonite, there is a highly significant difference between mean concentrations in the coarse as compared to the fine fractions. Table 6 shows that each environment exhibits a greater concentration of aragonite in the coarse fraction than it does in the fine. The inverse relationship is illustrated by the concentrations of high-Mg calcite.

The interaction term between environments and size fractions is nonsignificant in the cases of both aragonite and high-Mg calcite. A nonsignificant interaction indicates that the magnitude of difference between coarse and fine fractions is the same in all environments with respect to these two parameters. Fig. 7 compares the mineralogy of the sand and silt-clay fractions. The diagrams illustrate a shift toward enrichment of high-Mg calcite in the silt-clay fraction. Both statistical tests and the aforementioned figure indicate a reduction of aragonite and corresponding increase of high-Mg calcite in the fine fraction.

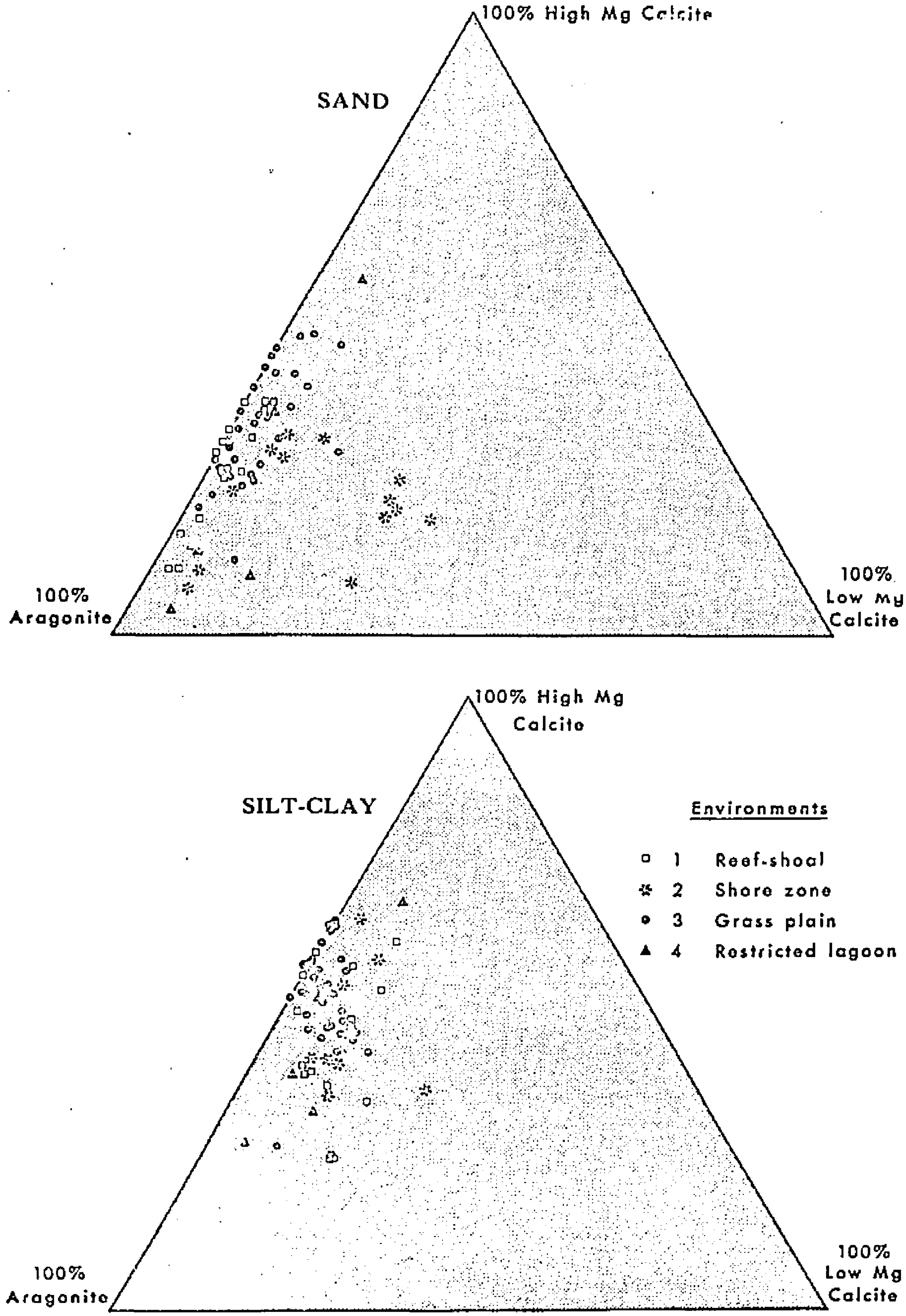


Fig. 7. Mineralogy of the sand and silt-clay fractions of samples collected from North Sound.

Differences in mean low-Mg calcite concentrations between environments are highly significant. This variation arises from a higher mean concentration of low-Mg calcite in the shore zone than in other North Sound environments (Table 6).

The low-Mg calcite data set shows a significant interaction term between environment and size fraction. The relative difference in mean concentration of low-Mg calcite in the sand fraction as compared to the silt-clay fraction is not the same among environments. Table 6 shows that mean concentrations are higher in the fine than in the coarse grain sizes for sediments of all environments except the shore zone. The sand fraction in this environment contains more low-Mg calcite than does the silt-clay fraction and is primarily responsible for the significant interaction term.

SEDIMENT CHEMISTRY

Table 8 presents analysis of variance summary statistics for tests of the variables Mg, Na, and Sr. Adjusted main effects and interactions for each data set are given in Table 9.

Significant differences exist between environments and size fractions for all three variables. The means of Table 9 are inspected in order to establish where differences arise.

With respect to Mg, the greatest differences in mean concentration occur between the grass plain and restricted

TABLE 8

ANALYSIS OF VARIANCE SUMMARY OF CATION CONCENTRATIONS

SOURCE OF VARIATION	df	Mg Mean Square	Mg F-Ratio	Sr Mean Square	Sr F-Ratio	Na Mean Square	Na F-Ratio
Environments	3	45.1	5.8**	705.4	11.8**	580.0	39.7**
Size Fractions	1	1077.0	139.1**	2269.1	38.0**	92.8	6.3*
Interaction	3	3.8	0.5	101.2	1.7	19.9	1.4
Error	129	7.7		59.7		14.6	
Total	136						

** Significant at the .01 Confidence Level.

* Significant at the .05 Confidence Level.

TABLE 9

MATRIX OF ADJUSTED MEANS AND MAIN EFFECTS FOR CATION CONCENTRATIONS (PPM BY WEIGHT)

VARIABLE		ENV. 1*	ENV. 2*	ENV. 3*	ENV. 4*	SAND	SILT-CLAY
Mg (10^{-3})	Environment	12.6	11.4	13.2	10.0		
	Sand	9.6	7.5	9.6	6.8		
	Silt-Clay	15.6	15.2	16.8	13.2		
	Size Fraction					8.4	15.2
Sr (10^{-2})	Environment	55.6	49.5	48.4	40.4		
	Sand	63.1	54.3	54.2	42.1		
	Silt-Clay	48.0	44.7	42.6	38.7		
	Size Fraction					53.4	43.5
Na (10^{-2})	Environment	27.5	18.6	19.0	23.5		
	Sand	27.5	17.5	18.5	21.0		
	Silt-Clay	27.5	19.7	19.4	26.0		
	Size Fraction					21.1	23.2

* Environments: 1. Reef-Shoal, 2. Shore Zone, 3. Grass Plain, 4. Restricted Lagoon.

lagoon. The significant difference between size fractions results from a higher concentration of Mg in the silt-clay than in the sand fraction in all environments.

Sediments of the reef-shoal exhibit the greatest concentration of Sr, whereas restricted lagoon sediments are least concentrated in this cation. The shore zone and grass plain have intermediate mean Sr values.

A significant difference exists between the mean Sr content of the sand fraction as compared to the silt-clay fraction. Table 9 shows that this difference arises from a greater concentration of Sr in the sand-sized sediments than in the fine fraction for all environments.

The data set for Na shows a highly significant mean variation between environments, but the difference between size fractions is significant only at the .05 level. Reef-shoal samples are much higher in mean Na concentration than lagoonal samples, but the difference in Na concentrations between the sand and silt-clay fractions is not great.

Interactions between environments and size fractions are not significant for the data sets of all three cations. Therefore, the magnitude of difference between coarse and fine fractions is the same within each environment with respect to the mean concentration of the three variables.

INTERPRETATION OF RESULTS

INTRODUCTION

The following sections contain an interpretation of results; emphasis is on the changing characteristics of surface sediments from one environment to another and the properties of the coarse, as compared to the fine-sized, fraction. Some basic changes in sediments as a function of sedimentary environment are incorporated into a simplified model of recent intrabasinal carbonate sedimentation under shallow marine conditions.

DIFFERENCES BETWEEN ENVIRONMENTS

Excluding the reef-shoal environment, constituent particle composition of the sand fraction is a reasonable indicator of in situ sedimentation relatively free of hydrologic influences. Within the reef-shoal environment high-energy conditions have shifted sand-sized particles from their site of origin. Fig. 8 shows the volumetric changes in sand-sized constituent particles on selected profiles across North Sound. These data were compiled from thin-section point counts. Mineralogy and acid-leach cation concentrations are presented in conjunction with constituent particle data.

Sediments of the reef-shoal are primarily sand sized with very little associated fines. The sands are composed of a diversity of grain types, some of which are locally

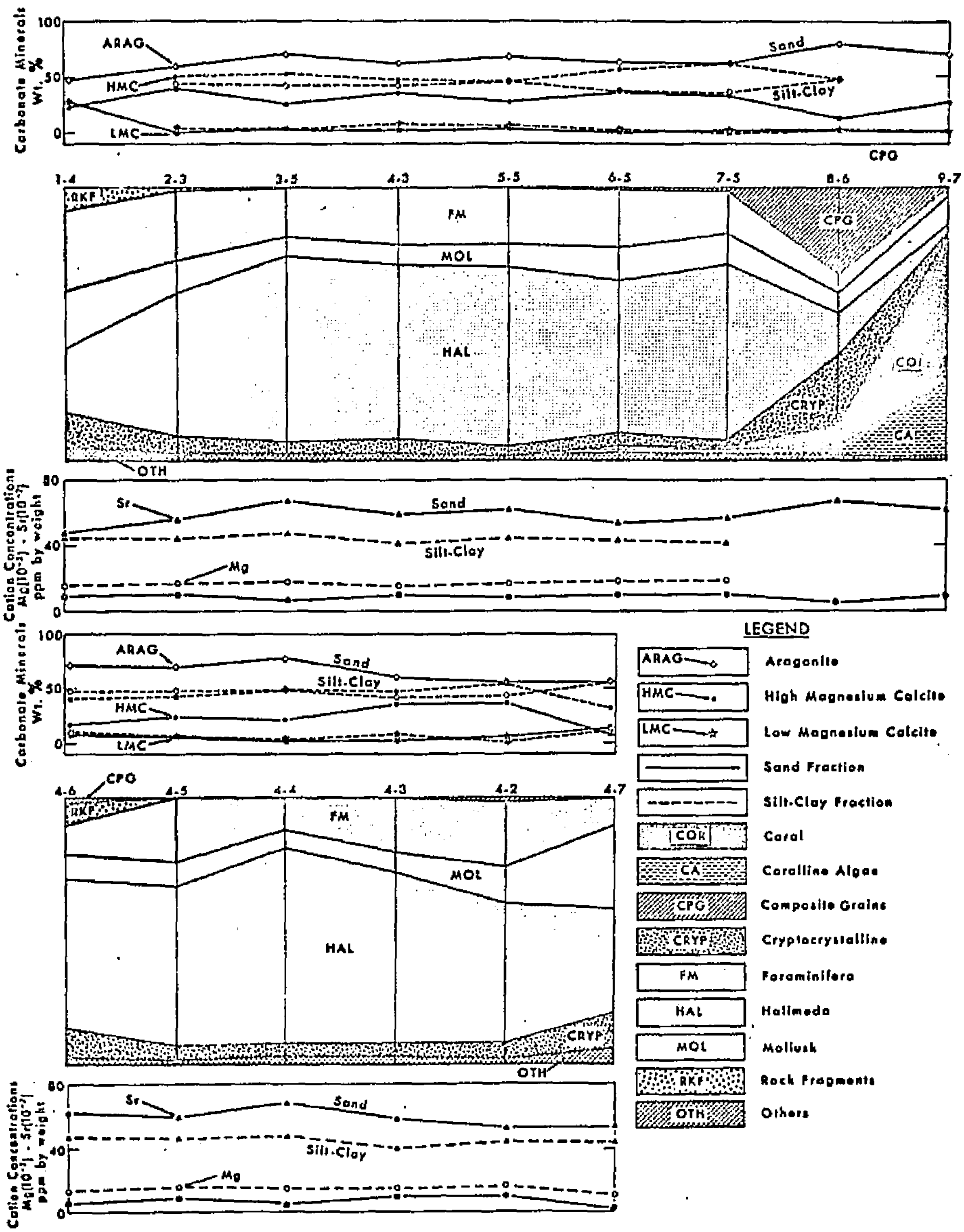


Fig. 8. Distribution of constituent particles, mineralogy, and cation concentrations across North Sound.

concentrated within the environment. Grain types which most typify reef-shoal sediments are aragonitic forms, coral and composite grains, and coralline algae, which are abundant sources of high-Mg calcite. Reef-shoal sediments contain a high percentage of these grains as compared to the sediments of the remaining environmental subdivisions of North Sound.

A spectrum of composite grain types is concentrated in response to small areas of active carbonate precipitation. Prominent breaks in the fringing reef across North Sound offer avenues of interaction between oceanic and lagoonal waters. It is within small localized areas lagoonward of these major channels through the reef that concentrations of composite grains occur. Among the composite grains are the grapestones described by Purdy (1963).

Sediments near the reef are composed of significantly smaller concentrations of Foraminifera, Halimeda, and molluscs than are other sediments. Coral and coralline algae which typify reef-shoal sediments, are primarily products of mechanical and biological destruction of the reef community. Purdy (1963) has shown that the occurrence of coral can be highly correlated with the occurrence of coralline algae. Among the quantitatively important constituents of Bahaman sands, these two grain types have the highest mutual occurrence. North Sound appears to be substantially the same. Coralline algae encrust the bases of coral colonies and pieces of coral rubble which form the structural framework of the reef. Debris spread lagoonward of the reef crest on the rubble flat is also generously coated by coralline algae.

For proper interpretation of mineralogic and trace cation concentrations, analyses of carbonate skeletons from the most common marine organisms found in North Sound are established as points of reference. Table 10 illustrates the types of skeletons tested and the resulting mineral and cation concentrations. High Mg and Sr concentrations are related to carbonate skeletons composed of calcite and aragonite, respectively. Chave (1954) has shown that in calcareous marine organisms only calcite contains abundant magnesium. Hoskin (1968) illustrates that Sr can be positively correlated with the abundance of aragonitic organisms, such as coral and calcified green algae. Not all aragonite is high in Sr, however, Table 10 shows that molluscan skeletons exhibit Sr concentrations considerably less than do corals and calcareous algae.

Mineralogically, the reef-shoal sediments are highly aragonitic and are second only to the grass plain in relative proportions of high-Mg calcite. The aragonite is derived primarily from coral and Halimeda. Incidence of these two grain types, both of which are composed of high-Sr aragonite (Table 10), results in proportionately higher Sr concentrations in reef-shoal sediments than in other environments. High-Mg calcite is contributed primarily by coralline algae and encrusting Foraminifera. Minor sources of this mineral are echinoids, serpulids, and alcyonarian spicules. Reef-shoal

TABLE 10

CATION CONCENTRATIONS AND MINERALOGY OF CARBONATE SKELETONS COMMON TO THE SEDIMENTS OF NORTH SOUND

ORGANISMS	SAMPLE	MINERALOGY	METHOD OF ANALYSIS	Na (10^{-3})	Mg (10^{-4})	Sr (10^{-3})	LOCATION	WORKERS
ALGAE	*Goniolithon strictum*	High Mg Calcite	AA	3.9	6.0	4.9	Grand Cayman	This study
ALGAE	*Halimeda* sp.	Aragonite	AA	1.85	1.2	8.8	Grand Cayman	This study
ALGAE	*Halimeda opuntia*	Aragonite	AA			8.5	Hogsty Reef	JDM
ALGAE	*Penicillus dumetosus*	Aragonite	AA			7.9	Brit. Honduras	RKM
ALGAE	*Rhipocephalus phoenix*	Aragonite	AA			8.0	Brit. Honduras	RKM
CORALS	*Acropora palmata*	Aragonite	AA	4.8	0.65	8.5	Grand Cayman	This study
CORALS	*Acropora cervicornis*	Aragonite	AA			7.3	Brit. Honduras	RKM
CORALS	*Montastrea annularis*	Aragonite	AA	6.0	0.54	7.5	Grand Cayman	This study
CORALS	*Porites divaricata*	Aragonite	AA	5.3	1.80	8.0	Grand Cayman	This study
CORALS	*Porites porites*	Aragonite	FP			8.7	Dry Tortugas	HTO
ECHINOID	*Diadema* sp.	High Mg Calcite	AA	5.1	3.8	2.1	Grand Cayman	This study
FORAMINIFERA	*Homotrema rubra*	High Mg Calcite	AA	4.0	3.01	2.5	Grand Cayman	This study
HYDROZOAN	*Millepora alcicornis*	Aragonite	AA	5.1	0.12	8.3	Grand Cayman	This study
MOLLUSCS	*Cerithium* sp.	Aragonite	AA			1.6	Grand Cayman	This study
MOLLUSCS	*Cerithium erythraense*	Aragonite	XF	4.3	0.11	1.5	Red Sea	GMF
MOLLUSCS	*Codakia* sp.	Aragonite	AA			1.7	Grand Cayman	This study
MOLLUSCS	*Cypraea turdus*	Aragonite	XF	5.2	0.07	1.3	Red Sea	GMF
MOLLUSCS	*Laevicardium* sp.	Aragonite	AA			1.6	Grand Cayman	This study
MOLLUSCS	*Strombus gigas*	Aragonite	AA	4.7	0.03	1.2	Brit. Honduras	RKM

Chemical Data in ppm by weight
AA – atomic absorption
FP – flame photometer
XF – X-ray fluorescence

GMF – G. M. Friedman 1968
RKM – R. K. Matthews 1966
JDM – John D. Milliman 1967
HTO – H. T. Odum 1957

sediments are intermediate between the highest concentrations, in the grass plain, and the lowest concentrations, in the restricted lagoon. Mg concentrations conform to the trend established by mineralogy. Fig. 8 further illustrates that Mg and Sr concentrations vary directly with proportion of high-Mg calcite and aragonite, respectively.

Although reef-shoal sediments concentrate Na to a greater extent than do the sediments in other parts of the basin, there appears to be no preferential concentration caused by mineralogy, as with Mg and Sr (Table 10).

The contour map of Fig. 9 illustrates the fact that high Na concentrations near the reef give way to progressively lower concentrations lagoonward. Billings and Ragland (1968) found a similar trend derived from analysis of skeletal sediments from the British Honduras Shelf. Rucker and Valentine (1961) report a positive correlation between salinity and the Na concentration in shells of *Crassostrea virginica*. Skeletons of dominant sediment-producers were analyzed for Na content. All specimens with the exception of molluscs were collected from the reef-shoal. It is evident from inspecting Na values in Table 10 that various biota from the same environments differentially concentrate Na in their carbonate skeletons. Sediments of the reef-shoal are composed primarily of coral and coralline algae, whereas those of the interior lagoon are characterized by calcareous green algae, molluscs, and Foraminifera. Corals have relatively high Na contents. *Halimeda* concentrates relatively small quantities of Na as

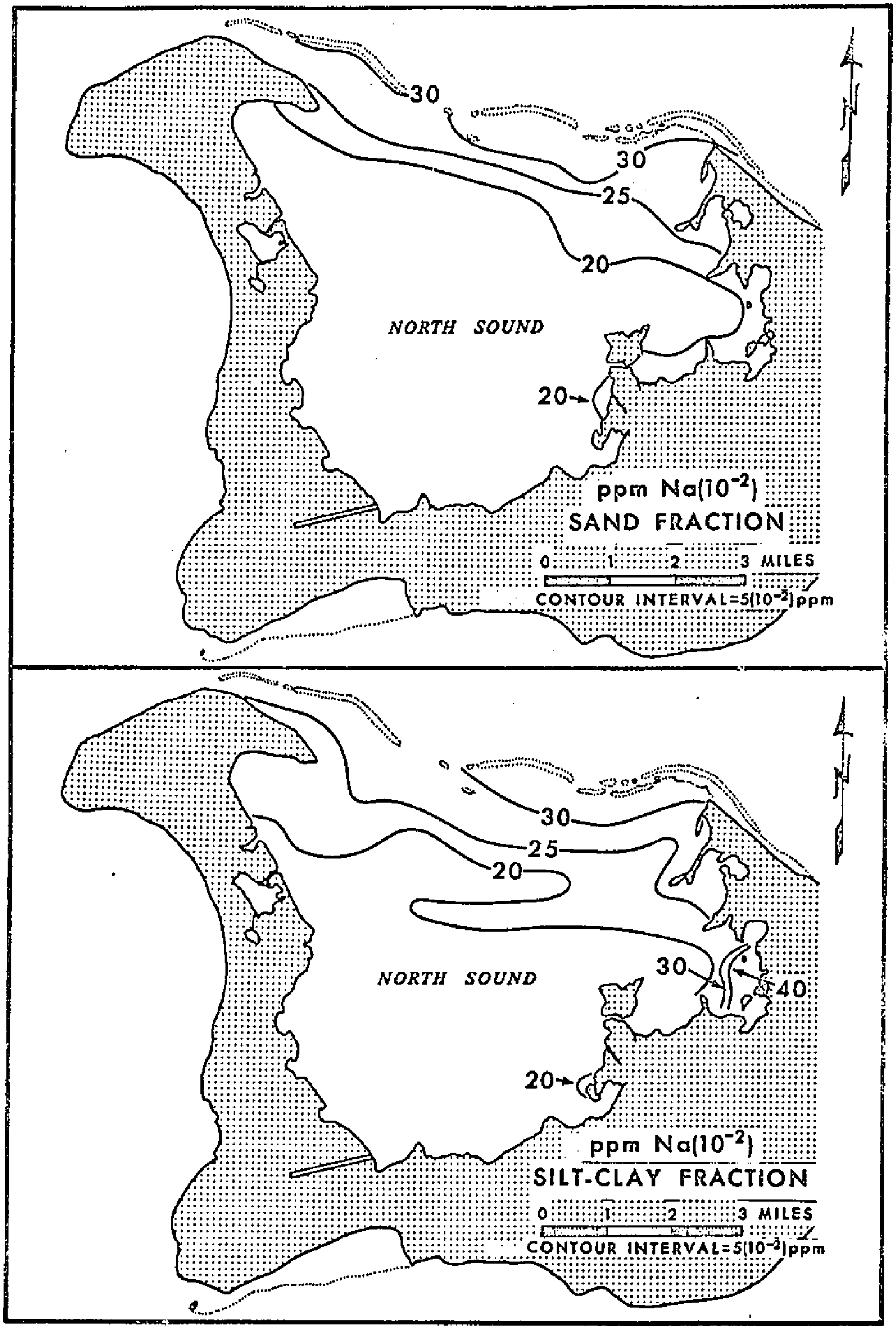


Fig. 9. Contour map of Na concentrations in the sand and silt-clay fractions.

compared to most other grain types. Proportions of these two constituent grains primarily control bulk Na differences between sediments of North Sound's environments. Therefore, the trend toward a high concentration of Na near the reef, as compared to the lagoon results primarily from an abundance of coral in reef-shoal sediments and Halimeda in lagoonal sediments. Water samples taken from various areas of North Sound confirm the lack of a well-defined salinity gradient. The Na trend, therefore, appears to be the resultant of various grain suites in which constituent grain types differentially accept Na into their structures.

The thin sediment cover of the shore zone may be characterized as having a proportionately higher concentration of low-Mg calcite than the sediments of North Sound's other environmental subdivisions. The occurrence of this carbonate mineral results from the incidence of two grain types, rock fragments and cryptocrystalline grains. These grains are products of erosion of the lithified sound floor and limestone outcrops adjacent to the shore zone. Rock fragments are composed of diagenetically altered limestone whose constituent particles (Plate 1). These cryptocrystalline grains occur as both aragonite and low-Mg calcite, depending on the degree of exposure to fresh water and subsequent diagenetic alteration. Diagenesis proceeds toward a stable carbonate mineral phase, low-Mg calcite. These changes account for the comparatively low aragonite and Na concentrations.

The relatively fine-grained sediments of the grass plain contain appreciable <u>in situ</u> derived sand-sized components. <u>Halimeda</u> and Foraminfera are grain types which most characterize the coarse fraction and distinguish the grass plain sediments from other environments (Fig. 8). With the exception of some radial hyaline varieties, most Foraminifera of the grass plain have high-Mg calcite tests. The most abundant types, peneroplids and miliolids, are high-Mg calcite. Corresponding to the occurrence of a large proportion of Foraminifera, grass plain sediments are highest in high-Mg calcite and Mg concentration of the four environmental subdivisions of North Sound. Cryptocrystalline and composite grains are rare in grass plain sediments.

Quiet-water sediments of the restricted lagoon are most aragonitic and lowest in high-Mg calcite and Mg concentration of any of North Sound's four major environments. An increase in molluscan grains (aragonite) at the expense of Foraminifera (high-Mg calcite) is responsible for this trend (Fig. 8). It is significant to note that even though sediments of this environment are highly aragonitic, Sr concentration is low. The low Sr content of mollusc aragonite compared to high Sr skeletal aragonite is corals and calcareous green algae (Table 10) accounts for the Sr depletion.

The above discussion illustrates the differences in sediment characteristics that occur between environments. Variation in sediment chemistry and mineralogy also occurs as a function of grain size.

DIFFERENCES BETWEEN SIZE FRACTIONS

Fig. 7 graphically illustrates and Tables 6 and 9 statistically confirm the consistent chemical and mineralogical difference between size fractions. In addition, Fig. 6 illustrates the general covariant relationship of coarse and fine sediment composition between environments. The principal difference between the sand and silt-clay-sized fractions is an enrichment of high-Mg calcite at the expense of aragonite in the fine-grained sizes. This relationship prevails in all of North Sound's four major environments. Relative differences in high-Mg calcite and aragonite concentrations between size fractions are the same throughout the study area. Mg and Sr concentrations are generally controlled by the abundance of high-Mg calcite and aragonite, respectively. The fines, therefore, show a significant increase in Mg concentration, and the coarse fraction is Sr.

A surplus of high-Mg calcite in the fine fraction of recent carbonate sediments has been reported by Matthews (1966), Berner (1967), and Weber (1967). In each study evidence was presented to support a decrease in aragonite and an increase in high-Mg calcite with decreasing grain size. Two general explanations could account for this phenomenon: (1) aragonite is preferentially removed from the fines, effectively increasing the proportion of high-Mg calcite, or (2) high-Mg calcite is being added to the fines more rapidly than aragonite. It it is assumed that aragonite is being selectively dissolved from the fines, leaving high-Mg calcite as a solution lag, one must explain why the more soluble phase, high-Mg calcite, does not go into solution more rapidly than aragonite. Goldsmith et al. (1955) and others show experimentally that at surface temperatures and pressures, high-Mg calcite is the most thermodynamically metastable carbonate mineral phase, low-Mg calcite is the least metastable, and aragonite is intermediate. Stehli and Hower (1961) have found this same stability sequence in nature under near-surface conditions. The possibility of preferential solution of aragonite becomes less likely in view of the fact that within the same basin of deposition aragonite is being actively precipitated, forming a variety of composite grains. The solution of fine-grained aragonite and high-Mg calcite is relatively common in the literature from both field and laboratory observations, but the solution of aragonite without even greater solution of high-Mg calcite is not well documented in theory or from field evidence.

Three general mechanisms are possible is addition of high-Mg calcite is considered to be responsible for the increased proportion of this mineral in the fine as compared to the coarse sediment fraction: (1) physical chemical precipitation, (2) high-Mg calcite microfossils flooding the fine-grained sizes, and (3) differential rates at which particles of varying mineralogy are physically reduced in size.

The high-Mg calcite mineral phase is well documented as being biogenically derived in recent carbonate sediments. Organisms which have skeletal parts composed of high-Mg calcite and are common to the sediments of North Sound are coralline algae (Chave, 1962); Foraminifera (Blackmon and Todd, 1959); and alcyonarian spicules and echinoids (Stehli and Hower, 1961). Precipitation of this mineral in fine-grained sizes by inorganic processes is not well known. Although precipitation of aragonite is commonly thought to be partially responsible for aragonitic muds, especially of the Bahama Bank, (Cloud, 1962 and others), inorganic precipitation of high-Mg calcite has not been well documented. At surface temperatures and pressures nonbiogenic precipitation of high-Mg calcite from normal sea water is virtually unknown. Therefore, physical chemical precipitation is not considered a probable mechanism for addition of fine-grained high-Mg calcite.

If the mineralogical imbalance between the coarse and fine fractions is considered caused by a microorganism with a high-Mg calcite test, then an abundance of whole tests would be expected in the fines. Foraminifera are very frequent grain types in the sand-sized sediments (Fig. 8), and would be likely candidates for prolific occurrence in the fines. Peneroplids and miliolids, however, are the most common varieties. They are primarily concentrated in the medium sand sizes. Qualitative data collected from inspection of the silt fractions of many samples under a binocular microscope showed frequencies of occurrence of whole Foraminifera to be low. Additional grain types such as ostracods or alcyonarian spicules were not numerous enough to be seriously considered as a source for the increased proportion of high-Mg calcite in the fines. There was no attempt to identify calcareous microorganisms smaller than silt-sized. Pelagic algae, such as coccolithophores, may be a possible source of calcium carbonate for the fine-grained sizes; however, Chave (1954) states that these forms are primarily composed of stable low-Mg calcite. Therefore, there is no compelling evidence to suggest that a sizeable addition of high-Mg calcite is being made to the fines by a microorganism silt sized or smaller.

If it is assumed that differential physical particle size reduction is responsible for the difference in high-Mg calcite content with grain size, then it must be shown that components of the sediment composed of high-Mg calcite are less durable than aragonite and low-Mg calcite grains. Chave (1964) studied the resistance of various types of carbonate skeletal materials to physical abrasion. He concluded that the least durable forms are those whose skeletons have much openwork and organic matrix -- echinoderms, bryozoa, algae. Most of these nondurable skeletal materials are composed of high-Mg calcite, especially echinoderms and coralline algae. Although Foraminifera were not included in the abrasion studies, it is safe to assume that their inherently fragile tests would yield to even minor abrasional stresses.

Matthews (1966) considers their delicate structure and subsequent nondurable nature as one of the most important factors in the production of lime mud on the British Honduras Shelf. Each environment of North Sound contains sediment-producing organisms capable of manufacturing appreciable quantities of high-Mg calcite. Fig. 8 shows that sand-sized sediments of the reef-shoal contain two major sources of high-Mg calcite, Foraminifera and coralline algae. Foraminifera are the main contributors to the lagoonal environments. Echinoids, alcyonarian spicules, and other minor sources are primarily concentrated in near-reef areas.

A supply of high-Mg calcite is available in both the reef-shoal and lagoonal portions of North Sound, and grains composed of this calcite mineral are generally less durable than aragonite or low-Mg calcite grains. If processes are available to reduce particles in size, then a mechanism for producing an abundance of high-Mg calcite in fine grain sizes may be suggested.

Processes responsible for particle size reduction in the reef-shoal environment are:

1. physical abrasion induced by current and wave energy
2. abrasional activities of grazing organisms
3. boring activities by clams, gastropods, algae, and sponges
4. mastication and ingestion by browsing organisms.

Processes responsible for particle size reduction in the lagoonal environment are:

1. physical abrasion by burrowing and vagrant benthonic organisms
2. mastication and ingestion by sediment-feeding organisms
3. boring activities primarily by algae.

These various physical and biological mechanisms for reducing particle size offer genetic implications concerning the fine-grained sediments of North Sound and a general explanation for variation of mineralogy with grain size.

ORIGIN OF MUDS

Properties of muds found in North Sound strongly suggest that they are primarily products of <u>in situ</u> degradation of larger carbonate skeletons. Inorganic precipitation of mud-sized carbonate material seems doubtful. The abundance of high-Mg calcite gives the fine fraction an unlikely composition for carbonate material precipitated directly from sea water. The general lack of oolites, beachrock, and other coated grains indicates an absence of basinwide physical-chemical precipitation among sand-sized constituents. Although localized areas of recent cementation result in the formation of composite grains, this cementation is not a widespread activity. Muds for all parts of the sound contain large proportions of Mg and high-Mg calcite. As pointed out by Chave (1954), direct chemical precipitation of calcite with Mg in the structure at seawater temperatures and surface pressures has not been reported. Muds which are primarily products of direct chemical precipitation are biased toward aragonite and not toward high-Mg calcite. Although the fines undoubtedly contain needles of aragonite similar to those postulated by Cloud (1962) as being products of physical chemical precipitation, Lowenstam (1955) has shown that they may be derived from algal species. Stockman et al. (1967) point out that disintegration of green algae with skeletal elements of calcium carbonate can be important in lime-mud formation. Because of their rapid seasonal growth and decomposition, calcified green algae are capable of producing sizeable accumulations of aragonitic mud.

Current and wave-induced abrasion certainly accounts for the production of silt-and clay-sized particles in the reef-shoal environment. Especially in areas near the reef, physical abrasion can be the cause of the production of fines, as suggested by Folk and Robles (1964). This process is complemented by biological activity which structurally weakens carbonate skeletal materials and makes them more susceptible to mechanical breakage and abrasion. The boring habits of clams and the sponge Cliona are of considerable consequence in the destruction of reef communities (Goreau and Hartman, 1963). Algae may also play a significant role in deteriorating carbonate skeletal materials. Hoskin (1963) suggests that filamentous green algae are very important boring organisms instrumental in weakening grain structure.

Other than by boring, fine-grained carbonates can be produced organically by the grazing action of parrot fish, echinoids, gastropods, and other marine organisms. Ingestion of sediment by holothurians, marine worms, and other organisms results in mud-sized material (Hoskin, 1963). Very little quantitative data are available concerning these activities.

In areas of mud accumulation where current and wave activity is not great enough to cause significant mechanical abrasion of particles, the combined boring and burrowing habit of organisms causes appreciable abrasion and breakage among fragile carbonate grains (Matthews, 1966). Marine worms and molluscs appear to be the two most active burrowing organisms of North Sound.

That the muds of North Sound are products of a source outside the basin of deposition is unlikely. The isolated nature of the island and its low-lying topography make erosion and transportation of appreciable quantities of carbonate detritus into North Sound improbable.

Although the fine-grained sediments of North Sound are undoubtedly of mixed origin, the covariance of the sand and silt-clay fractions with respect to mineralogy and chemistry (Fig. 8) suggests that the fines are primarily the products of <u>in situ</u> degradation of larger particles. Near-reef areas exhibit both mechanical and biological processes for the production of fine-grained particles. In quiet water areas, biological processes must account for most particle size reduction and production of mud-sized carbonate material.

MODEL FOR INTRABASINAL CARBONATE SEDIMENTATION UNDER SHALLOW MARINE CONDITIONS

Diff rences in samples drawn from contemporaneously deposited sediments may be considered as a basis for erecting a predictive model of variation in intrabasinal carbonate sediments. By analysis of recent sediments as a function of environment of deposition, a genetic relationship between carbonate sediments and intrabasinal environments may be established. The following discussion outlines the composite variation measured in recent sediments collected from North Sound, Grand Cayman Island, and constitutes a simplified model of intrabasinal carbonate sedimentation under shallow marine conditions.

The most obvious variation in sediments of a basin such as North Sound is textural. Two major subdivisions of the basin can be delineated, reef-shoal and lagoon. It is easily recognized that a transition exists from sands near the reef to muds in the lagoon. Further environmental subdivisions can be made in both areas, but high energy conditions in the near-reef areas cause mixing of sediments. Therefore, more refined environmental distinctions in this area are hampered. Subdivisions within the lagoon are: (a) shore zone, (b) lagoon interior (grass plain), and (c) restricted areas. Sediments from each of these areas have distinctive characteristics.

Grain suites characteristic of areas near the reef include coral, coralline algae, and composite grains. These grains are practically excluded from the lagoonal environments. The localized occurrence of composite grains may suggest the position of areas of active interchange between lagoonal and oceanic waters, resulting in the inorganic precipitation of carbonate cements. The occurrence of sediments whose sand fraction is composed primarily of calcareous green algae, Halimeda, and Foraminifera strongly suggests lagoonal conditions. Rock fragments locally incorporated into a lagoonal grain suite suggest erosion of pre-existing limestone in areas near the margin of the basin. These grain types may be useful as shoreline indicators. Restricted lagoonal areas may possibly be distinguished by a proportionate increase in mollusc grains as compared to open lagoon conditions.

Although the sediments from all portions of the lagoon are highly aragonitic, the restricted areas may have the highest proportion of aragonite owing to an increased mollusc population and subsequent decrease in high-Mg calcite Foraminifera. The least aragonitic and highest low-Mg calcite portions of the basin would be those influenced by the erosional products of pre-existing limestones. High-Mg calcite is likely to be most concentrated in the lagoon interior where the sediments contain an abundant proportion of Foraminifera.

Mg and Sr concentrations conform generally to the relative abundance of high-Mg calcite and aragonite, respectively. Sr, however, is more concentrated in coral and calcareous algae aragonite than in molluscan aragonite.

Distinctions of near-reef and lagoonal environments on Sr concentrations may be doubtful if the lagoon contains a high content of calcareous green algae. These aragonitic forms concentrate Sr to approximately the same degree as corals of the reef environments. Na, to the contrary, is much more concentrated in corals and other members of the reef community than in calcareous algae of the lagoon.

In a shallow-water marine basin (10 to 15 feet) where solution of fine-grained carbonates plays little or no role in altering the fine-fraction composition, mineral and chemical properties of the fines do not simply mirror those of the coarse fraction. Differential rates of particle size reduction bias the fines toward the composition of the least physically durable grains in the sand sizes. Grains composed of high-Mg calcite are most susceptible to degradational processes which produce fine from coarser particles. Therefore, the fine fraction is enriched in this carbonate mineral, while aragonite is effectively reduced. The inverse of this mineralogy is true of coarse grain sediments.

In conjunction with the chemistry and mineralogy of the fine fraction, it can be stated that the muds accumulating in the basin's lagoonal environments are primarily products of degradation of carbonate skeletal materials. Although fine-grained carbonates may be carried from areas near the reef into the quiet water lagoon, especially during periods of abnormally high energy conditions, the lime muds are primarily formed by <u>in situ</u> processes.

Chemical and mineralogical data collected on recent carbonates may be of limited application in ancient limestones which have undergone extensive diagenesis. However, in some younger deposits (Tertiary to present) the line of investigation applied in this study may be directly used in making environmental determinations. Simply being aware of the possible initial differences in carbonate sediments both between environments and size fractions may offer insight into the course of subsequent diagenetic change.

CONCLUSIONS

Data collected from North Sound, Grand Cayman Island, lead to the following conclusions concerning the interaction of environments and carbonate sediments within a small, shallow marine basin of deposition.

1. It is possible to delineate four environments - (a) reef-shoal, (b) shore-zone, (c) grass plain, and (d) restricted lagoon on the basis of a combination of sediment parameters.

   (a) Reef-shoal---Coral, coralline algae, and recently cemented composite grains, plus the highest bulk sediment concentrations of acid-leachable Sr and Na, characterize reef-shoal sediments.

   (b) Shore-zone---Cryptocrystalline grains, and the highest concentrations of low-Mg calcite exemplify sediments of the shore-zone.

   (c) Grass plain---*Halimeda* and Foraminifera are the most characteristic constituent grains of this environment. The highest concentrations of high-Mg calcite and acid-leachable Mg are found in the grass plain and can be directly attributed to the large proportion of high-Mg calcite Foraminifera in the sediments.

   (d) Restricted lagoon---The greatest proportions of mollusc grains and aragonite distinguish the restricted lagoon.

2. Among the four environments of North Sound, the proportion of high-Mg calcite in the sediments is increased in

the fine fraction at the expense of aragonite. The changes in high-Mg calcite and aragonite concentrations between the coarse and fine fractions are proportionately the same in all environments. Differential rates of physical particle size reduction appear to be the most reasonable explanation for this phenomenon. High-Mg calcite components, especially Foraminifera, echinoids, and coralline algae, are being eroded more rapidly than aragonitic and calcitic skeletons.

3. In the very shallow (5 to 15 feet) marine conditions of North Sound, recent submarine cememtation results in the formation of composite grains. The formation and distribution of these grains are associated with localized areas in a coralgal sand apron lagoonward of major passages through the fringing reef. The mechanism which triggers precipitation of aragonite is apparently related to the vigorous interaction of oceanic and lagoonal waters.

4. Use of Sr and Mg as environmental indicators without supporting constituent particle data may not be very effective in sediments similar to those of North Sound. Corals from areas near the reef and Halimeda of the lagoon have similar Sr concentrations. Coralline algae plus Foraminifera in sediments from the reef result in combined Mg concentrations similar to the large proportions of Foraminifera in lagoonal sediments.

5. Although the muds of North Sound may have a mixed origin, most fine-grained sediments are derived in situ by processes of skeletal degradation.

6. A well-defined gradient exists for Na concentrations in North Sound sediments. Sediments near the reef which have the highest Na concentrations are transitional with lagoon sediments with lower Na contents. These bulk sediment concentrations apparently reflect differential acceptance of Na in the carbonate lattice by various skeletal grains rather than response to a factor such as salinity.

The available data point out that even in small basins with relatively uncomplicated and distinctive depositional environments the distribution and character of carbonate sediments is extremely complex. A significant point suggested by the data which may have paleoenvironmental significance is that fines generated primarily in situ may vary considerably from chemical and mineralogical properties of the coarse fraction, without evoking the necessity of selective solution or addition of a carbonate mineral phase. Methods used in this study may not be directly applicable to ancient limestones which have undergone extensive diagenetic changes. However, in relatively young carbonates in which diagenetic changes have been slight, the techniques of this study may be directly applied for making paleoenvironmental interpretations.

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VITA

Harry Heil Roberts was born on February 2, 1940, in Huntington, West Virginia. He attended elementary and secondary school in Milton, West Virginia, and in September 1958 he entered Marshall University. In May of 1962 he graduated from that institution with a Bachelor of Science degree in Physics.

In the fall of 1963 he entered Louisiana State University as a graduate student in the Department of Geology, where he had been awarded a graduate assistantship. He was elected as associate member of Sigma Xi and was the recipient of the Pan American Petroleum Foundation, Inc., Fellowship in Geology for the academic year 1964-65.

In January 1966 he was awarded a Master of Science degree in the Department of Geology at Louisiana State University. Upon graduation he entered Brigham Young University in Provo, Utah, where he studied for one year. While attending Brigham Young University he was awarded a NASA Traineeship in geology. During February 1967 he was granted a graduate assistantship and returned to Louisiana State University to conclude a Ph.D. degree in Geology. The summer of 1967 was spent on Grand Cayman Island collecting data for a dissertation. The field season was sponsored by Coastal Studies Institute, with whom he is presently associated.

He is married to the former Mary Sue Hamb and at present they have one son, Andrew Bradley.

APPENDIX

APPENDIX 1

CONSTITUENT GRAIN PERCENTAGES OF SAND FRACTION

Sample Numbers	Grain Types*											
	1	2	3	4	5	6	7	8	9	10	11	12
1-1	0.7	0.2	0.9	21.0	0.9	2.6	5.8	5.9	27.8	20.8	11.1	3.1
1-2	0.0	0.5	0.0	15.3	0.8	1.9	8.2	4.2	27.9	18.5	20.4	3.0
1-3	0.6	0.5	0.0	20.0	0.0	4.4	6.9	8.2	23.4	21.0	10.2	5.3
1-4	0.0	0.3	0.0	12.6	0.2	3.5	17.4	10.2	23.0	20.5	8.1	4.9
2-3	0.0	0.0	0.0	6.0	0.4	5.0	13.8	7.3	52.9	11.1	1.2	2.9
2-4	0.6	0.0	0.0	5.2	0.0	5.3	15.5	7.5	45.9	17.1	0.0	3.5
2-5	0.0	0.3	0.0	7.6	0.0	6.6	18.3	7.3	37.0	18.1	1.5	3.9
2-6	0.0	0.3	0.0	21.1	0.2	3.5	8.3	4.6	25.8	19.2	8.3	9.3
3-1	0.0	0.4	0.0	12.5	0.0	2.6	14.3	3.6	38.6	16.1	8.7	4.0
3-2	0.4	0.3	0.7	4.9	0.0	8.9	14.9	8.1	46.5	14.2	0.0	1.6
3-3	0.2	0.4	1.0	6.4	0.3	3.5	6.4	2.3	65.0	13.6	0.4	1.4
3-4	0.5	0.0	0.7	12.4	0.9	9.4	12.4	10.1	16.1	29.9	2.2	6.1
3-5	0.0	0.0	0.0	4.4	0.3	7.2	4.9	5.7	68.4	7.0	0.0	2.6
3-6	0.7	0.0	0.0	6.9	0.3	2.9	8.7	2.9	60.9	14.3	0.0	2.9
4-2	1.6	0.0	0.2	6.3	0.5	5.6	10.2	8.2	51.7	13.8	0.0	2.4
4-3	0.3	0.0	0.0	5.0	0.5	8.2	5.2	8.3	63.6	6.6	0.0	3.0
4-4	0.5	0.0	0.0	4.7	0.0	3.4	4.9	3.7	73.4	7.3	0.0	2.8
4-5	0.4	0.0	0.0	4.9	0.0	8.5	9.5	6.7	59.8	9.3	0.0	1.4
4-6	1.3	0.3	0.0	10.9	0.2	2.4	6.3	2.7	55.0	8.6	8.0	3.0
4-7	1.1	0.0	0.5	12.4	0.0	0.8	2.4	3.3	38.9	31.4	3.8	5.9
5-1	2.0	0.0	0.0	5.9	0.5	1.9	1.2	3.9	73.4	7.5	0.6	3.7
5-2	0.7	0.0	0.0	5.5	0.0	6.9	7.1	5.0	62.0	11.7	0.0	1.7
5-3	0.0	0.2	0.0	4.4	0.0	6.9	8.2	3.8	64.4	10.9	0.0	1.7
5-4	0.0	0.0	0.0	5.4	0.3	9.3	6.8	5.8	61.7	8.6	0.0	2.6
5-5	0.3	0.0	0.0	3.5	0.2	4.2	11.2	5.9	65.5	8.4	0.0	1.2

APPENDIX 1 (CONTINUED)

CONSTITUENT GRAIN PERCENTAGES OF SAND FRACTION

Sample Numbers	Grain Types*											
	1	2	3	4	5	6	7	8	9	10	11	12
5-6	0.0	0.2	0.0	3.7	0.9	2.9	6.0	5.0	62.4	17.6	0.0	1.9
5-8	0.0	0.0	0.0	4.0	0.0	1.2	6.7	3.3	61.2	21.5	0.0	2.7
6-1	0.0	2.7	0.7	15.9	0.0	0.8	1.4	2.3	50.3	12.7	10.9	2.9
6-2	0.2	0.2	1.0	3.7	1.0	2.8	5.8	2.8	67.3	14.8	0.0	1.0
6-3	0.2	0.0	0.0	7.3	1.2	5.4	13.2	8.4	52.3	10.8	0.3	1.6
6-4	0.0	0.0	0.4	5.2	0.0	2.8	7.2	5.4	72.6	5.7	0.0	1.1
6-5	0.8	0.0	1.7	4.6	1.3	5.2	9.9	6.2	56.1	12.0	0.0	2.8
6-6	0.3	0.4	5.1	3.4	0.4	6.4	14.9	6.8	51.8	9.0	0.0	2.3
6-7	0.3	0.7	3.8	3.7	0.2	6.8	15.7	5.4	46.0	15.9	0.0	2.1
7-1	2.0	0.2	0.5	4.0	0.0	3.5	11.2	5.3	47.2	19.2	3.7	3.9
7-2	0.2	0.0	0.0	3.8	0.0	2.5	5.6	6.6	73.2	6.8	0.0	1.8
7-3	0.0	0.0	0.0	1.1	0.0	2.2	6.5	4.9	73.4	10.1	0.0	2.4
7-4	0.0	0.3	1.8	1.1	0.0	2.3	8.5	4.3	70.4	9.8	0.5	1.5
7-5	0.8	0.5	1.8	1.6	0.0	2.7	8.8	7.2	64.9	10.6	0.0	2.0
7-6	1.0	0.2	10.9	2.2	0.3	4.5	11.0	8.5	49.6	10.6	0.0	2.0
7-7	0.8	2.2	8.9	4.4	0.0	5.8	12.2	12.9	28.8	14.2	0.1	10.5
8-1	1.6	0.2	2.5	4.1	0.0	1.9	0.4	0.6	75.6	9.3	2.9	1.7
8-2	0.0	1.2	1.4	4.1	0.4	2.9	13.6	11.0	48.6	13.4	1.6	2.3
8-3	0.2	0.6	1.1	3.1	0.0	3.8	16.4	6.5	61.1	6.2	0.0	1.9
8-4	0.1	0.8	3.9	2.5	0.0	1.2	10.1	4.2	67.8	9.1	0.0	0.9
8-5	1.6	0.9	3.8	5.6	0.6	3.1	10.0	9.8	55.8	8.1	0.0	1.2
8-6	32.8	7.7	2.5	25.3	0.5	0.8	1.9	4.0	15.8	6.9	0.4	2.9
8-7	22.0	11.3	5.8	21.8	0.0	0.2	1.9	3.4	10.4	12.3	5.4	6.3
8-8	3.0	32.5	15.7	8.0	1.9	1.4	5.7	9.3	11.4	5.6	0.0	6.6
9-1	0.8	0.9	3.1	6.6	0.2	2.1	9.9	6.5	45.3	19.6	3.3	2.6
9-2	0.0	0.0	1.1	8.7	1.3	3.3	19.1	7.4	46.3	11.0	0.2	2.2
9-3	0.4	5.1	6.7	21.5	0.2	1.3	10.0	5.4	36.0	8.4	0.6	5.3

APPENDIX 1 (CONTINUED)

CONSTITUENT GRAIN PERCENTAGES OF SAND FRACTION

Sample Numbers	Grain Types*											
	1	2	3	4	5	6	7	8	9	10	11	12
9-4	4.0	35.1	7.0	7.1	0.0	0.0	1.0	0.1	32.0	11.7	0.0	2.7
9-5	11.2	12.3	9.9	11.6	0.3	0.2	2.4	1.2	34.4	15.8	0.5	1.2
9-6	15.0	17.9	6.8	12.3	1.4	0.2	6.8	6.0	17.2	11.6	0.0	4.7
9-7	0.1	53.5	27.0	0.9	1.8	0.0	1.2	0.8	3.4	10.9	0.0	1.3
9-8	0.6	34.3	14.2	7.0	1.0	1.6	5.4	5.5	13.8	12.7	0.0	3.3
9-9	0.0	52.6	16.0	5.0	4.4	0.3	1.4	3.3	4.7	7.9	0.0	5.1
10-1	2.1	1.9	6.7	5.4	1.3	3.9	3.4	7.4	42.6	22.5	1.3	2.2
10-2	0.3	5.4	5.0	9.2	0.7	6.5	17.6	6.6	31.3	13.6	0.6	4.2
10-3	1.4	7.5	11.8	18.3	0.2	0.5	10.3	4.2	28.9	10.6	2.0	5.3
11-1	0.2	14.6	11.1	15.7	1.0	2.0	4.1	3.5	36.5	9.0	0.0	3.0
11-2	0.9	48.0	14.5	3.1	4.3	0.8	3.5	1.6	13.1	8.9	0.0	2.1
12-1	0.3	33.6	16.7	7.8	3.4	1.2	5.8	6.3	10.6	8.2	0.0	7.7

* Grain Types:

1 Composite Grains
2 Coral
3 Coralline Algae
4 Cryptocrystalline Grains
5 Encrusting Foraminifera
6 Miliolids
7 Peneroplids
8 Other Foraminifera
9 Halimeda
10 Molluscs
11 Rock Fragments
12 Others

APPENDIX 2

CARBONATE MINERAL PERCENTAGES

	Sand Fraction			Silt-Clay Fraction		
Sample Numbers	Aragonite	High-Mg Calcite	Low-Mg Calcite	Aragonite	High-Mg Calcite	Low-Mg Calcite
1-1	51.0	20.6	28.4	----	----	----
1-2	51.0	21.6	27.4	----	----	----
1-3	53.0	18.8	28.2	----	----	----
1-4	48.0	25.0	27.0	----	----	----
2-2	----	----	----	44.0	44.2	11.8
2-3	60.0	40.0	0.0	45.0	51.2	3.8
2-4	61.0	31.6	7.4	43.0	47.3	9.7
2-5	54.0	30.4	15.6	43.0	45.6	11.4
2-6	47.0	18.6	34.4	39.0	36.6	24.4
3-1	55.0	31.5	13.5	41.0	53.1	5.9
3-2	53.0	40.0	7.0	47.0	51.9	1.1
3-3	66.0	27.2	6.8	43.0	46.7	10.3
3-4	45.0	46.8	8.2	45.0	45.1	9.9
3-5	71.0	25.5	3.5	43.0	53.0	4.0
3-6	77.0	12.0	11.0	47.0	42.4	10.6
4-1	----	----	----	63.0	27.0	10.0
4-2	57.0	36.6	6.4	44.0	54.9	1.1
4-3	62.0	35.7	2.3	43.0	47.3	9.7
4-4	78.0	20.7	1.3	48.0	48.4	3.6
4-5	70.0	24.1	5.9	48.0	44.7	7.3
4-6	72.0	18.2	9.8	48.0	40.6	11.4
4-7	76.0	9.6	14.4	55.0	32.9	12.1
5-1	83.0	10.7	6.3	53.0	35.3	11.7
5-2	68.0	25.0	7.0	46.0	46.4	7.6
5-3	66.0	33.3	0.7	44.0	52.8	3.2
5-4	69.0	29.1	0.9	44.0	56.0	0.0
5-5	69.0	28.2	2.8	46.0	46.4	7.6

APPENDIX 2 (CONTINUED)

CARBONATE MINERAL PERCENTAGES

Sample Numbers	Sand Fraction Aragonite	Sand Fraction High-Mg Calcite	Sand Fraction Low-Mg Calcite	Silt-Clay Fraction Aragonite	Silt-Clay Fraction High-Mg Calcite	Silt-Clay Fraction Low-Mg Calcite
5-6	68.0	25.6	3.8	43.0	51.9	5.1
5-7	90.0	4.2	5.8	67.0	26.7	6.3
5-8	82.0	13.1	4.9	55.0	38.7	6.3
6-1	63.0	8.1	28.9	49.0	41.3	9.7
6-2	75.0	22.8	2.8	49.0	51.0	0.0
6-3	61.0	35.1	3.9	43.0	51.9	5.1
6-4	72.0	26.3	1.7	44.0	56.0	0.0
6-5	64.0	36.0	0.0	39.0	57.3	3.7
6-6	57.0	43.0	0.0	39.0	55.5	5.5
6-7	60.0	36.4	3.6	45.0	51.2	3.8
6-8	37.0	57.3	5.7	26.0	66.6	7.4
7-1	63.0	30.0	7.0	44.0	45.4	10.6
7-2	72.0	28.0	0.0	49.0	45.9	5.0
7-3	72.0	26.3	1.7	43.0	49.0	8.0
7-4	72.0	28.0	0.0	43.0	55.9	1.1
7-5	63.0	34.4	2.6	37.0	63.0	0.0
7-6	54.0	41.9	4.1	38.0	62.0	0.0
7-7	48.0	48.4	3.6	37.0	63.0	0.0
8-1	86.0	7.6	6.4	51.0	41.7	7.3
8-2	54.0	46.0	0.0	40.0	60.0	0.0
8-3	55.0	45.0	0.0	43.0	57.0	0.0
8-4	67.0	33.0	0.0	45.0	55.0	0.0
8-5	60.0	36.4	3.6	43.0	57.0	0.0
8-6	82.0	14.4	3.6	49.0	49.0	2.0
8-7	79.0	18.9	2.1	53.0	40.0	7.0
8-8	59.0	37.3	3.7	36.0	52.5	11.5

APPENDIX 2 (CONTINUED)

CARBONATE MINERAL PERCENTAGES

	Sand Fraction			Silt-Clay Fraction		
Sample Numbers	Aragonite	High-Mg Calcite	Low-Mg Calcite	Aragonite	High-Mg Calcite	Low-Mg Calcite
9-1	62.0	28.5	9.5	34.0	57.4	8.6
9-2	50.0	48.0	2.0	43.0	57.0	0.0
9-3	65.0	31.5	3.5	43.0	46.2	10.8
9-4	87.0	10.8	2.2	53.0	39.0	8.0
9-5	86.0	10.8	3.2	49.0	42.3	8.7
9-6	83.0	16.3	0.7	51.0	37.2	11.8
9-7	72.0	28.0	0.0	----	----	----
9-8	69.0	26.0	5.0	56.0	25.1	18.9
9-9	60.0	37.6	2.4	56.0	25.1	18.9
10-1	60.0	32.0	8.0	33.0	64.3	2.7
10-2	56.0	42.2	1.8	37.0	63.0	0.0
10-3	69.0	26.0	5.0	38.0	56.4	5.2
11-1	73.0	25.1	1.9	30.0	60.2	9.8
11-2	63.0	27.0	10.0	52.0	38.9	9.1
12-1	72.0	26.8	1.2	47.0	34.5	18.5

APPENDIX 3

CATION CONCENTRATIONS (PPM BY WEIGHT)

Sample Numbers	Sand Fraction Mg (10^{-3})	Sand Fraction Sr (10^{-2})	Sand Fraction Na (10^{-2})	Silt-Clay Fraction Mg (10^{-3})	Silt-Clay Fraction Sr (10^{-2})	Silt-Clay Fraction Na (10^{-2})
1-1	9.5	48.5	17.0	13.0	45.0	17.5
1-2	8.7	51.0	17.5	13.8	50.9	16.8
1-3	7.8	46.5	18.5	15.4	45.0	19.0
1-4	9.5	46.5	16.5	15.4	44.0	18.5
2-1	3.1	29.0	18.5	14.3	29.9	14.8
2-2	8.3	25.0	19.5	17.2	27.5	21.5
2-3	10.5	55.5	17.0	16.5	44.0	18.0
2-4	8.7	52.0	19.0	15.6	43.5	18.5
2-5	11.0	47.0	17.0	15.0	43.5	20.0
2-6	7.7	50.0	16.5	12.8	46.0	17.5
3-1	10.4	50.0	17.5	17.0	43.5	18.5
3-2	12.5	51.0	17.0	15.0	47.0	18.0
3-3	7.8	63.0	17.0	16.0	43.0	18.5
3-4	13.9	42.0	19.0	15.8	44.0	18.0
3-5	6.4	67.0	18.0	17.3	44.5	18.0
3-6	3.5	48.5	21.5	15.0	40.0	17.0
4-1	3.5	58.0	17.0	10.8	39.0	19.0
4-2	11.0	53.0	19.0	16.5	44.0	17.5
4-3	10.4	59.0	17.5	15.3	41.0	16.0
4-4	5.5	70.0	18.5	16.5	45.0	18.0
4-5	9.3	60.0	16.5	16.5	46.0	17.5
4-6	5.6	63.0	16.0	14.7	47.5	17.5
4-7	2.8	54.0	21.5	10.9	44.5	17.5
4-8	4.7	29.9	23.2	----	----	----
4-9	5.7	21.8	25.0	----	----	----
5-1	3.3	68.0	17.0	11.9	49.0	18.0

APPENDIX 3 (CONTINUED)

CATION CONCENTRATIONS (PPM BY WEIGHT)

Sample Numbers	Sand Fraction			Silt-Clay Fraction		
	Mg (10^{-3})	Sr (10^{-2})	Na (10^{-2})	Mg (10^{-3})	Sr (10^{-2})	Na (10^{-2})
5-2	7.7	59.5	17.5	16.0	46.0	17.5
5-3	9.0	62.0	17.0	16.5	45.0	18.0
5-4	8.7	63.0	18.0	17.8	44.5	18.5
5-5	8.6	62.0	17.0	16.2	45.0	17.5
5-6	7.8	59.5	18.5	16.0	41.5	19.0
5-7	7.1	53.0	17.0	10.0	43.0	19.0
5-8	3.5	64.0	19.0	12.0	39.5	49.0
6-1	4.0	56.0	20.5	15.2	48.0	19.5
6-2	7.0	63.0	17.5	16.2	48.0	18.0
6-3	10.4	53.0	17.0	17.6	44.5	20.0
6-4	7.4	63.0	17.5	17.5	45.0	22.5
6-5	10.9	53.5	20.0	18.0	43.0	24.0
6-6	13.4	50.0	20.5	19.2	40.0	21.0
6-7	10.9	49.0	20.5	16.8	43.0	21.5
6-8	16.2	23.0	21.0	16.2	23.5	23.0
7-1	8.7	52.5	18.0	16.4	42.5	18.5
7-2	7.3	59.0	18.5	15.6	45.5	16.0
7-3	8.3	59.0	18.0	16.4	44.0	16.0
7-4	8.2	59.5	19.0	16.3	44.0	18.5
7-5	10.7	56.0	18.5	19.0	42.0	19.0
7-6	15.4	49.5	20.5	19.8	40.0	23.0
7-7	15.7	42.0	25.5	19.6	41.5	27.5
8-1	2.9	68.0	17.0	13.8	49.0	17.5
8-2	14.7	49.5	19.0	19.5	41.5	22.5
8-3	12.5	51.0	17.5	17.6	44.0	22.0
8-4	9.5	49.5	18.0	16.4	45.0	18.0
8-5	13.2	52.0	20.0	18.2	43.0	26.5

APPENDIX 3 (CONTINUED)

CATION CONCENTRATIONS (PPM BY WEIGHT)

Sample Numbers	Sand Fraction			Silt-Clay Fraction		
	Mg (10^{-3})	Sr (10^{-2})	Na (10^{-2})	Mg (10^{-3})	Sr (10^{-2})	Na (10^{-2})
8-6	5.4	68.0	30.5	----	----	----
8-7	13.0	64.0	25.5	12.6	58.0	29.1
8-8	12.5	56.0	27.5	12.2	51.1	24.4
9-1	9.5	52.5	16.5	19.1	36.0	37.0
9-2	12.5	47.5	17.0	17.9	44.0	23.5
9-3	10.9	59.5	24.0	18.5	42.5	26.0
9-4	6.8	67.0	26.5	----	----	----
9-5	6.9	65.0	30.0	15.6	49.5	29.5
9-6	6.2	76.0	31.0	13.6	51.5	31.0
9-7	9.5	62.0	31.5	----	----	----
9-8	9.7	66.0	29.5	15.4	51.5	32.0
9-9	12.0	58.0	32.0	12.0	53.0	33.0
10-1	10.5	54.0	19.0	19.5	35.0	20.0
10-2	13.3	54.0	22.5	20.5	40.0	24.5
10-3	9.1	70.0	28.0	18.0	43.0	26.0
11-1	7.8	72.5	28.0	21.8	38.0	24.5
11-2	9.4	64.5	29.5	13.5	51.5	29.0
12-1	11.8	60.0	29.0	14.1	47.0	29.0

APPENDIX 4

FORAMINIFERA COMMON TO NORTH SOUND

1. *Acervulina inhaerens* Schultze
2. *Amphistegina lessonii* d'Orbigny
3. *Archaias angulatus* (Fichtel & Moll)
4. *Articulina mucronata* (d'Orbigny)
5. *Asterigerina carinata* d'Orbigny
6. *Brizalina lowmani* (Phleger & Parker)
7. *Brizalina* sp.
8. *Clavulina* sp.
9. *Clavulina tricarinata* d'Orbigny
10. *Cribroelphidium poeyanum* (d'Orbigny)
11. *Cymbaloporetta squammosa* (d'Orbigny)
12. *Florilus atlanticus* (Cushman)
13. *Fursenkoina punctata* (d'Orbigny)
14. *Heterillina ornatissima* (Karner)
15. *Homotrema rubra* (Lamarck)
16. *Miliolinella subrotunda* (Montagu)
17. *Peneroplis proteus* d'Orbigny
18. *Peneroplis* sp.
19. *Planorbulina* sp.
20. *Pyrgo denticulata* (H. B. Brady)
21. *Pyrgo* sp.
22. *Quinqueloculina torrei* Acosta
23. *Rectobolivina* sp.
24. *Rosalina candeiana* d'Orbigny

APPENDIX 4 (CONTINUED)

FORAMINIFERA COMMON TO NORTH SOUND

25. Rotobinella mira (Cushman)
26. Rotorbinella rosea (d'Orbigny)
27. Sagrina pulchella d'Orbigny
28. Sorites marginalis (Lamarck)
29. Spirolina acicularis (Batsch)
30. Spirolina arietina (Batsch)
31. Spiroloculina ornata d'Orbigny
32. Triloculina carinata d'Orbigny
33. Triloculina linneiana d'Orbigny
34. Triloculina quadrilateralis d'Orbigny
35. Triloculina rotunda d'Orbigny
36. Triloculina sp.
37. Valvulina oviedoiana d'Orbigny

EXAMINATION AND THESIS REPORT

Candidate: HARRY HEIL ROBERTS

Major Field: GEOLOGY

Title of Thesis: RECENT CARBONATE SEDIMENTATION NORTH SOUND, GRAND CAYMAN ISLAND, BRITISH WEST INDIES.

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Date of Examination:

May 1, 1969